PB-230 272

PLANT SCALE REGENERATION OF GRANULAR ACTIVATED CARBON

Gordon Culp, et al

Cornell, Howland, Hayes and Merryfield
Corvallis, Oregon

1 March 1966

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California - State Report
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PB 230 272

FINAL PROGRESS REPORT
USPHS DEMONSTRATION GRANT 84—01

PLANT SCALE REGENERATION OF GRANULAR ACTIVATED CARBON

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STUDIES DURING PERIOD OF APRIL 1, 1965—MARCH 1, 1966

February 1966

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This project was supported in part by Water Supply and Pollution Control Demonstration Grant 84—01 from the Public Health Service

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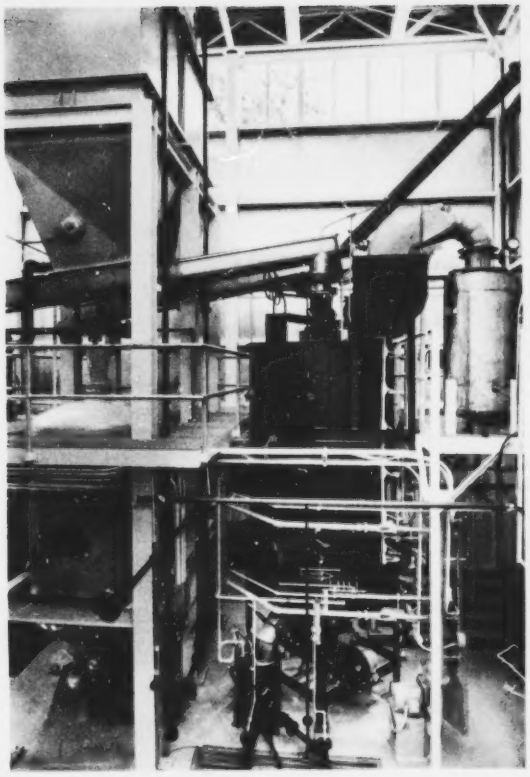

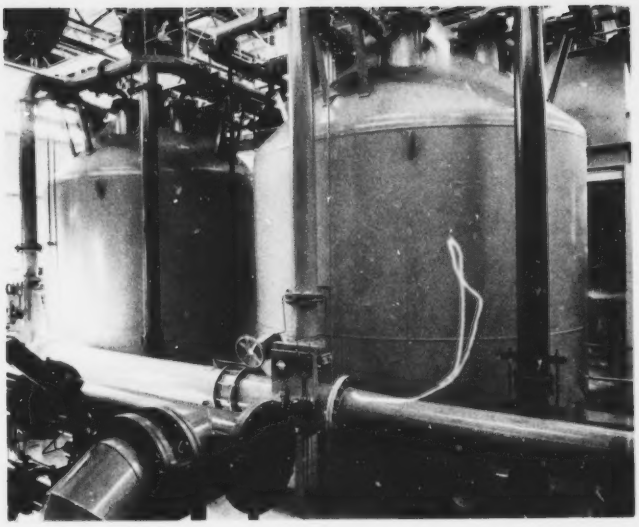

CARBON REGENERATION SYSTEM AT LEFT

PLANT CARBON COLUMNS ABOVE

PLANT EFFLUENT SAMPLES SHOWN BELOW LEFT

PILOT CARBON COLUMNS LOWER RIGHT

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SUMMARY

In treating chemically coagulated and filtered secondary sewage effluent, granular activated carbon columns operated as upflow countercurrent columns produced an effluent of consistently good quality. An average of 740 pounds of carbon per million gallons of waste water treated has been removed from the carbon columns and regenerated. High turbidity in the carbon column influent during the plant startup resulted in mechanical fouling of the carbon. It was found that by downflushing the columns that the adverse effects of mechanical fouling could be reduced and the carbon dose decreased. In addition, both pilot carbon column and main carbon column studies showed that the carbon dose can be reduced by increasing the contact time.

Pilot carbon column studies showed that the hydraulic loading in the range of 4.0 to 6.5 gpm/ft^2 does not significantly affect the adsorption process at a given contact time. A 12 x 40 mesh carbon was approximately 35 percent more efficient than an 8 x 30 mesh carbon for contact times up to 10 minutes. However, physical problems, such as excessive head loss and a greater susceptibility to mechanical fouling, limit the application of the 12 x 40 mesh carbon to an upflow column without modifying the existing column design.

Spent carbon removed for regeneration was found to dewater to equilibrium conditions (approximately 40 percent moisture) in one hour or less. Thermal regeneration of the spent carbon to virgin apparent density and Iodine Number was accomplished at temperatures of 1650-1680° F. with the addition of one pound of steam per pound of dry carbon. The energy required to obtain this degree of regeneration was 4,000 Btu per pound of dry carbon. The addition of steam to the regeneration furnace gave a more uniform distribution of hearth temperatures and permitted more complete regeneration of carbon at a given temperature and feed rate than without steam. Carbon losses are estimated to be less than 10 percent of the carbon regenerated.

While the carbon was regenerated to virgin characteristics with respect to apparent density and Iodine Number, pilot carbon column studies indicated that the first cycle regenerated carbon was at least 10 percent less efficient at contact times less than 11 minutes in adsorbing ABS than virgin carbon.

To date, the estimated cost of the activated carbon treatment at the South Tahoe PUD plant (2.5 mgd capacity) is $68.00 per million gallons. Under present conditions of operation, the cost of the chemical treatment and filtration preceding the carbon treatment is $98.25 per million gallons. These figures include amortization of capital costs.

THEORY

Activated carbon removes organic impurities from water by the process of adsorption. Adsorption may be defined[1] as the phenomenon whereby molecules adhere to a surface with which they come in contact. The fact that activated carbon has extremely large surface area per unit of volume makes it an efficient adsorptive material. The activation of carbon produces many pores in the carbon particles and it is the area of the walls within these pores that accounts for nearly all of the surface area of the carbon particles.

Upon contact with a water containing soluble organic materials, the activated carbon selectively removes these organic materials by adsorption. Activated carbon can be made from over 30 types of raw materials[2]. The carbons used in water treatment are usually derived from wood or coal. Carbons made from bituminous coal are hard and dense and can be pumped in a water slurry without any appreciable deterioration[3]. Carbons made from wood are usually not hard enough to be handled hydraulically. The physical strength of the carbon must be great enough to withstand the repeated handling procedures associated with the regeneration processes.

Thermal regeneration is the only known practical means of restoring virgin activity to carbon which has been used in water treatment[4]. The temperature of the spent carbon is raised to a point where the adsorbed organic materials are volatilized and a minimum amount of burning of the carbon occurs. Regeneration of granular carbon is generally accomplished in multiple-hearth furnaces or rotary kilns.

LITERATURE REVIEW

The use of carbon for purposes other than fuel is reported as early as 1550 B.C. when it was used for medicinal purposes[2]. The discovery of the phenomenon of adsorption, as now understood, is generally attributed to Scheele, who in 1773 described experiments on gases exposed to carbon[2]. The earliest documented use of carbon for removal of impurities from solutions is 1785 when Lowitz observed that charcoal would decolorize many liquids[2]. The first industrial application came a few years later when wood char was used in a refinery to clarify cane sugar[2].

During the last 40 years activated carbon has been used extensively in water treatment for the removal of taste and odor producing substances. During this period powdered carbon was used far more than granular activated carbon beds for water treatment. Since regeneration of granular activated carbon has been proven to be economical, granular activated carbon beds have been used in several instances[3, 4, 5, 6] for the control of tastes and odors in domestic water supplies. The use of granular carbon beds has two important advantages over the use of powdered carbon[5]. More efficient use can be made of carbon in the bed form than in the slurry form, and there is no need to continually check for the proper dose with carbon beds. Hassler[2] reports that for 137 municipalities using activated carbon for taste and odor control, the average carbon dose was 23 pounds per million gallons with a range of 4 to 429 pounds per million gallons.

The U.S. Public Health Service feels that the adsorptive process is the most promising of currently known methods for the further treatment of secondary sewage effluents[7]. Of course, the treatment of these effluents requires larger carbon doses than those normally used in water treatment. Because of the large quantities of carbon required, efficient regeneration of the carbon is a requirement for an economical waste water treatment system. To date, the use of granular activated carbon beds has received the most study for adsorption of organic materials from sewage effluents. Difficulty with the recovery and regeneration of powdered carbon has, so far, limited its application to sewage effluents.

Morris and Weber[8] have studied the adsorption process applied to materials commonly found in sewage effluents. They found that the rate of adsorption is a linear function of the square root of concentration of the material being adsorbed. Thus, the process favors the removal of trace quantities. They found that the rate of adsorption varied as the inverse square of the diameter of the carbon particles. As pointed out by Flentje and Hager[3], crushing the carbon particles to produce smaller particles enhances the rate of adsorption by exposing more entrances to the carbon pores. Because the carbon particle size primarily affects the rate of adsorption and not the capacity of the carbon, the difference in performance of columns containing different size carbons decreases as the contact time increases[12].

Morris and Weber[8] also found that the configuration of the adsorbate molecule affects the rate of adsorption. Molecules with highly branched structures are removed much more slowly than those of identical molecular weight but with a configuration that permits coiling or compactness. They found the rate of adsorption of ABS to increase with decreasing pH.

Joyce et al (9, 10) studied the treatment of a sand-filtered secondary effluent with granular activated carbon beds on a pilot scale. They found the required carbon dose to be a function of contact time for hydraulic loading rates in the range of 2.5 to 10 gpm/sq ft. The carbon dose varied from 500 to 830 pounds per million gallons of filtered secondary effluent treated. The chemical oxygen demand (COD) of the filtered secondary effluent was reduced from 50 to 70 mg/l to 12 to 20 mg/l by the carbon treatment. The remaining COD could not be reduced by increasing the carbon column contact time from 15 minutes to 37 minutes. The ABS content of the carbon column effluent was used as a control. When ABS reached 0.5 mg/l in the carbon column effluent, spent carbon was regenerated. The spent carbon removed for regeneration had adsorbed about 4 percent ABS by weight. The spent carbon was regenerated at 1740° F. using a 34 percent steam, 66 percent air atmosphere. Repeated regeneration (15 cycles) of the carbon reduced the total surface area as reflected by the decrease in Iodine Number from 942 for the virgin carbon to 782 at the end of the test. Some of the finer pores in the carbon were widened and the carbon showed a marked increase in ash, from 5.4 percent to 13.2 percent. The greatest portion of the ash was found to be acid soluble; thus, it was concluded that, if it should be necessary, the ash buildup in the regenerated carbon could be prevented by treatment of the carbon with acid following regeneration. Carbon losses averaged 4.6 percent per cycle of regeneration.

After 15 regeneration cycles, a column of regenerated carbon was operated in parallel with a column of virgin carbon. The column of regenerated carbon passed 32 percent less flow prior to ABS breakthrough than did the column of virgin carbon. Based upon their pilot plant data, Joyce et al[9] estimated the total cost of activated carbon treatment of secondary effluent to be $30 per million gallons for a 100 mgd plant, $70 per million gallons for a 10 mgd plant, and $130 per million gallons for a 1 mgd plant.

Davies and Kaplan[11] studied a pilot-scale adsorption system for sewage effluents using powdered carbon. Powdered carbon doses of 2,000 to 5,000 pounds per million gallons of secondary effluent were used. The powdered carbon was mixed with the effluent and the carbon was then flocculated with the aid of a polyelectrolyte and separated from the effluent in a sludge-blanket settling system. About 90 percent of the equilibrium capacity of the carbon was reached in a 5 minute mixing period. The carbon treated effluent COD was about 5 mg/l. The spent powdered carbon was regenerated in a steam atmosphere at 750° F., with a one hour deten-

tion in the furnace. The estimated cost of the powdered carbon treatment was $67 to $79 per million gallons for a 10 mgd plant, or about the same as the estimated cost of the granular carbon system[9]. Although powdered carbon can be very successfully regenerated in the laboratory, as shown by Davies and Kaplan[11], full-scale regeneration systems for powdered carbon have not been so successful. Sugar refineries attempted regeneration of powdered carbon for many years but finally abandoned the process because of the irregular recoveries (60 to 90 percent) of the regeneration process[2]. On the other hand, full-scale regeneration systems for granular carbon are widely used in the sugar industry with carbon losses of 5 percent used for design purposes. Five percent losses have been independently reported for granular regeneration systems used in municipal water treatment[4]. Although the data of Davies and Kaplan[11] indicate some potential advantages of a powdered carbon system (lower carbon regeneration temperature, effective treatment of unfiltered secondary effluent), the practicality of a full-scale powdered carbon recovery and regeneration system for waste water treatment has yet to be demonstrated.

The economics of the granular carbon adsorption system applied to waste water are dependent upon the efficiency of the regeneration process. The cost of the carbon added to replace that lost in the regeneration process may constitute more than 50 percent of the total cost of carbon treatment[10]. The available cost estimates for granular activated carbon treatment of waste water are based only on pilot-scale plants.

The remainder of this report consists of the findings on the first year of operation of the full-scale (2.5 mgd) activated carbon treatment of municipal waste water at South Lake Tahoe, California.

WATER RECLAMATION PROCESS

A tertiary sewage treatment process has been developed[13, 14] and a 2.5 mgd plant constructed at the South Tahoe (California) Public Utility District Water Reclamation Plant. The tertiary plant treats the effluent from a conventional activated sludge plant. The tertiary process, Figure 1, consists of coagulation of the secondary effluent with alum followed by filtration through two multi-media separation beds. The effluent from the separation beds flows upward through two carbon columns operated in parallel. These columns are 12 feet in diameter and have an effective carbon depth of 14 feet. Each column is charged with 25 tons of an 8 x 30 mesh activated carbon (Pittsburgh Chemical Company, Type SGL). The carbon columns are operated in a countercurrent manner so that effluent leaving the carbon columns is always in contact with the freshest carbon.

The water quality at various points in the secondary and tertiary treatment processes is shown in Table 1.

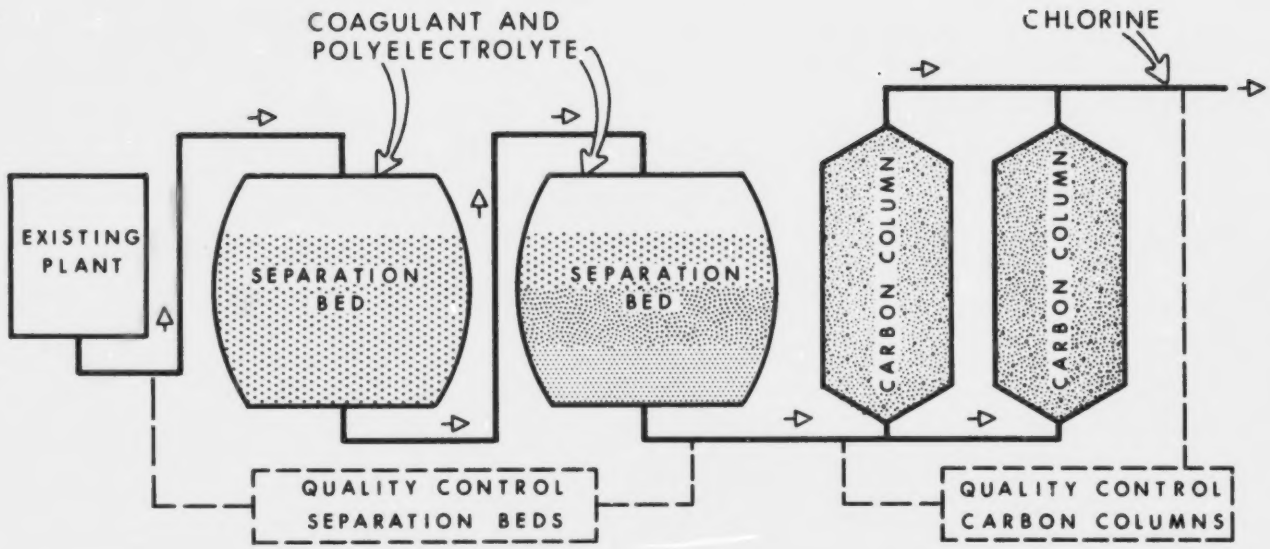

FIGURE 1

MAIN UNITS IN TERTIARY PROCESS

TABLE I

WATER QUALITY AT VARIOUS POINTS IN PROCESS

	Raw Sewage	Secondary Effluent	Separation Bed Effluent	Carbon Column Effluent
BOD, mg/l	200-400	20-100	<1	<1
COD, mg/l	400-600	80-160	30-60	3-25
Total Organic Carbon, mg/l	---	---	10-18	1-6
ABS, mg/l	2.0-4.0	1.1-2.9	1.1-2.9	<.01-0.50
PO_4, mg/l as PO_4	---	25-30	0.1-1	0.1-1
Color, units	---	---	10-30	<5
Turbidity, units	---	30-70	<0.5-3	<0.5-1
Nitrogen				
Organic N, mg/l as N	10-15	4-6	2-4	1-2
Ammonia N, mg/l as N	25-35	25-32	25-32	25-32
NO_3 and NO_2, mg/l as N	0	0	0	0
Unchlorinated				
Coliforms, MPN/100 ml	---	2,400,000	9,300	11,000
Fecal Coliforms, MPN/100 ml	---	150,000	930	930
Chlorinated				
Coliforms, MPN/100 ml	---	---	8.6	<2.1
Fecal Coliforms, MPN/100 ml	---	---	<2.1	<2.1

(Samples for analysis for virus were obtained from secondary effluent, separation bed effluent, and carbon column effluent, but the results are not available at this time.)

PILOT CARBON COLUMN STUDIES

Description of Pilot Carbon Columns. In order to study the efficiency of the main carbon columns and the carbon regeneration system, four pilot carbon columns (PCC) were constructed These columns were designed to operate in paralliel with the main carbon columns and at the same surface loading rate.

A one-inch tap was installed in the influent header to the main carbon columns. The separation bed effluent is pumped upwards through the four pilot carbon columns. The rate of flow to each column is regulated by a rotameter, 0 to 55 gph capacity, and the total volume of separation bed effluent passing through the columns is measured by a water meter.

These pilot columns are constructed of 4-inch diameter PVC pipe and have an effective depth of 14'-6", including pipe and couplings. (Figure 2) Six 1/4-inch sampling taps are provided to enable measurement of adsorbate concentrations at various carbon depths. A 4-inch diameter Neva-clog screen holds the carbon in place at the bottom of the column. A 30-mesh stainless steel screen is located at the top of the column. Provisions are made at the top and bottom of the column for the addition of fresh carbon and the removal of spent carbon.

About two days after the initial start-up of the pilot carbon columns, a rapid increase in the head loss across the pilot carbon columns was experienced. To determine if carbon fines were plugging the Neva-clog screens, originally installed as effluent screens, the effluent screens were removed. These screens were severely plugged with particles of carbon and attempts to remove the entrapped carbon fines were futile. As a result, the stainless steel screens described above were installed and were found to be satisfactory.

Experimental Procedures.

Run 1 - The initial head loss in the main carbon columns was considerably higher than anticipated. Because the initial carbon charge to the main columns was not washed in order to remove carbon fines which might have been generated during shipping, it was possible that excessive amounts of carbon fines were contributing to the high head loss in the main columns. One pilot carbon column (PCC 4) was charged with washed 8 x 30 mesh carbon to determine if carbon fines, which could be removed by washing, were contributing to the high head loss in the main columns.

Two pilot carbon columns (PCC 1 and 2) were charged with unwashed 8 x 30 mesh carbon, as were the main columns. These two pilot columns were to be operated at the same surface loading rate as the main columns. However, excessive head loss across these pilot columns reduced the flows

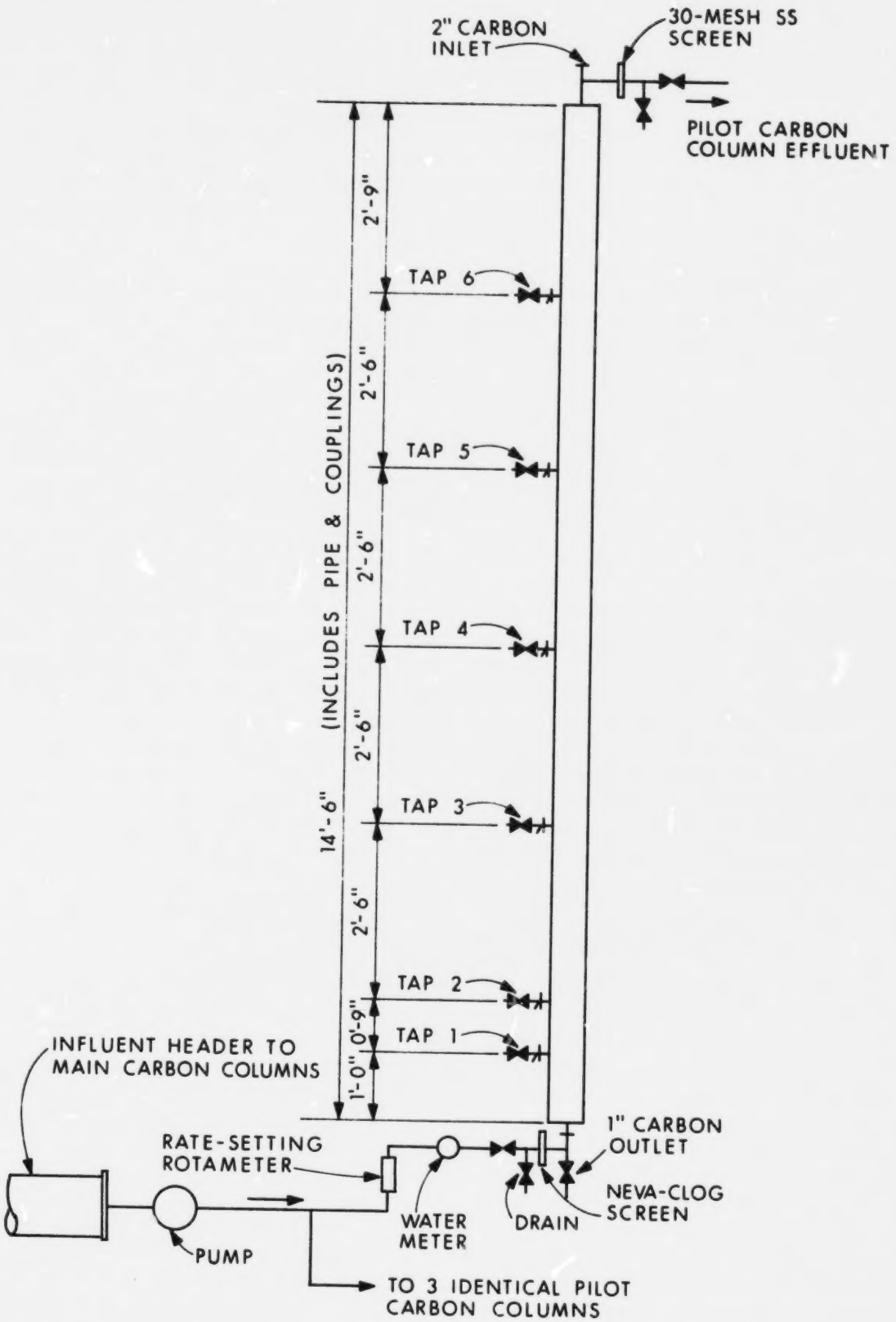

FIGURE 2

PILOT CARBON COLUMNS

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to such an extent that their loading was no longer in parallel with that being applied to the main columns. The flow through PCC 4, which contained washed 8 x 30 mesh carbon, was maintained at a rate comparable to that in the main columns. Thus, the data from PCC 1 and 2 will be compared with that from PCC 4 to determine the effects of the different loading rates on adsorption.

The remaining pilot column (PCC 3) was charged with unwashed 12 x 40 mesh carbon to measure the effect of carbon particle size on column performance. Three days after the pilot carbon effluent screens were changed, the flow through the 12 x 40 mesh carbon fell off. Inspection of the effluent screen showed that no fines were plugging the screen. The carbon was then removed from the column so that the column could be charged with washed 12 x 40 mesh carbon. It was found that the lower portion of the column was plugged with a fine floc. It is believed that this entrapped floc, as well as carbon fines, were contributing to the excessive head loss across the pilot columns and the main columns.

To alleviate high head loss problem, about 10 percent of the original carbon charge was removed from the main carbon columns and pilot carbon columns to obtain some freeboard for washing the carbon column and to allow room for expansion of the carbon during normal operation. It was found that the excessive amounts of head loss across the columns could be eliminated by occasionally downflushing the columns. Downflushing not only removed the carbon fines from the effluent screens, but washed the floc from the lower portion of the column. A considerable amount of floc was observed to be present in the backflush water emerging from the pilot carbon columns during the initial period of backflushing.

Run 2 - One pilot carbon column (PCC 5) was charged with virgin 8 x 30 mesh carbon and operated in parallel with another column (PCC 6) which was charged with regenerated 8 x 30 mesh carbon. The regenerated carbon used in PCC 6 was a composite sample of the regenerated carbon from the first carbon regeneration.

Pilot carbon column 4 which contained the washed 8 x 30 mesh carbon used in run 1 was operated in parallel with the main columns. Spent carbon was withdrawn and regenerated carbon added in the same proportions as in the main columns.

Sampling and Analyses. Composite samples of the separation bed effluent (carbon column influent) were collected daily. Grab samples were obtained from all the taps on a particular pilot carbon column every other day. Grab samples of the main carbon column effluent were obtained daily. In addition, a grab sample of the carbon column influent was obtained at the same time the pilot carbon column taps and main carbon columns were sampled.

All of these samples were analyzed for apparent alkyl benzine sulfonate (ABS), chemical oxygen demand (COD), and total organic carbon (TOC). Analyses for ABS and COD were performed by study personnel and the TOC analyses were performed by the U. S. Public Health Service, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio.

Experimental Results. The operational data obtained from the pilot carbon columns and main carbon columns are shown as breakthrough curves (Figures 3 - 12). Some of the COD and TOC sampling depths have been eliminated for the sake of clarity.

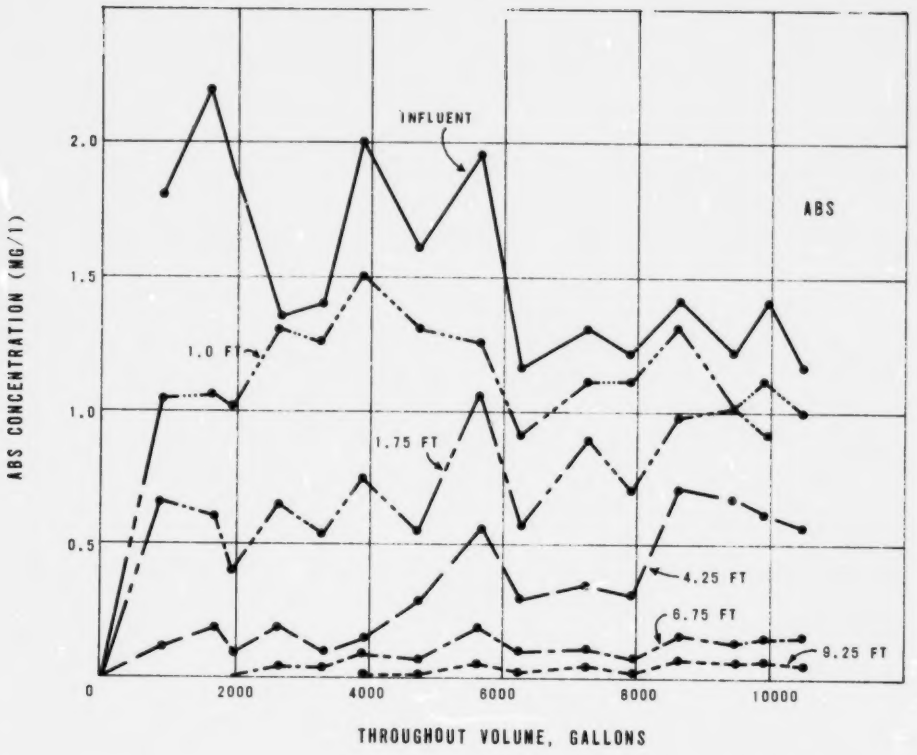
As previously mentioned, PCC 1 and 2 operated at a lower surface loading rate than the main carbon columns. Since PCC 1 and 2 were operated at essentially the same surface loading rate, only the results from PCC 2 will be presented. Data analysis showed no significance in the results obtained from PCC 1 and 2.

Pilot carbon columns 5 and 6, charged with virgin and one cycle regenerated 8 x 30 mesh carbon respectively, were operated in parallel. The operational data on PCC 5 and 6 are shown on Figures 9 - 12 as breakthrough curves for ABS and TOC.

Pilot carbon column 4 was to be operated in parallel with the main carbon columns, but mechanical problems with this pilot column eventually made it impossible to maintain a rate of flow parallel to that in the main carbon columns. The use of the pilot column had to be discontinued.

Discussion of Results.

Effect of Mechanical Fouling of Carbon - As previously discussed, a poor quality secondary effluent was being treated during the first run. As a result, the turbidity of the water applied to the carbon columns was higher than desired. The plugging of the columns with this turbidity (often more than one unit) was reflected by an increasing head loss across the columns with continued operation. This head loss could be reduced by backflushing the carbon columns to flush the entrapped floc from the bottom of the columns. In addition to increasing the head loss across the carbon columns, the turbidity trapped in the lower portions of the columns resulted in mechanical fouling of the carbon.



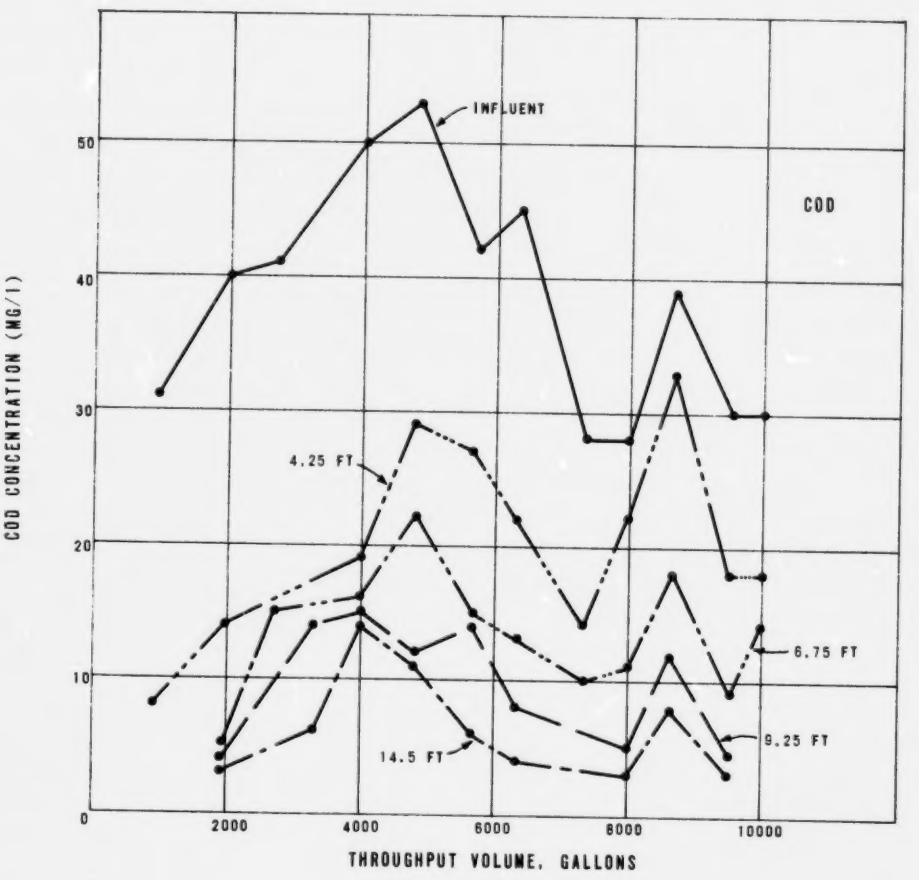


FIGURE 3
ABS AND COD BREAKTHROUGH CURVES FOR PCC 2
(8X30 MESH CARBON - 4.1 GPM/FT^2)

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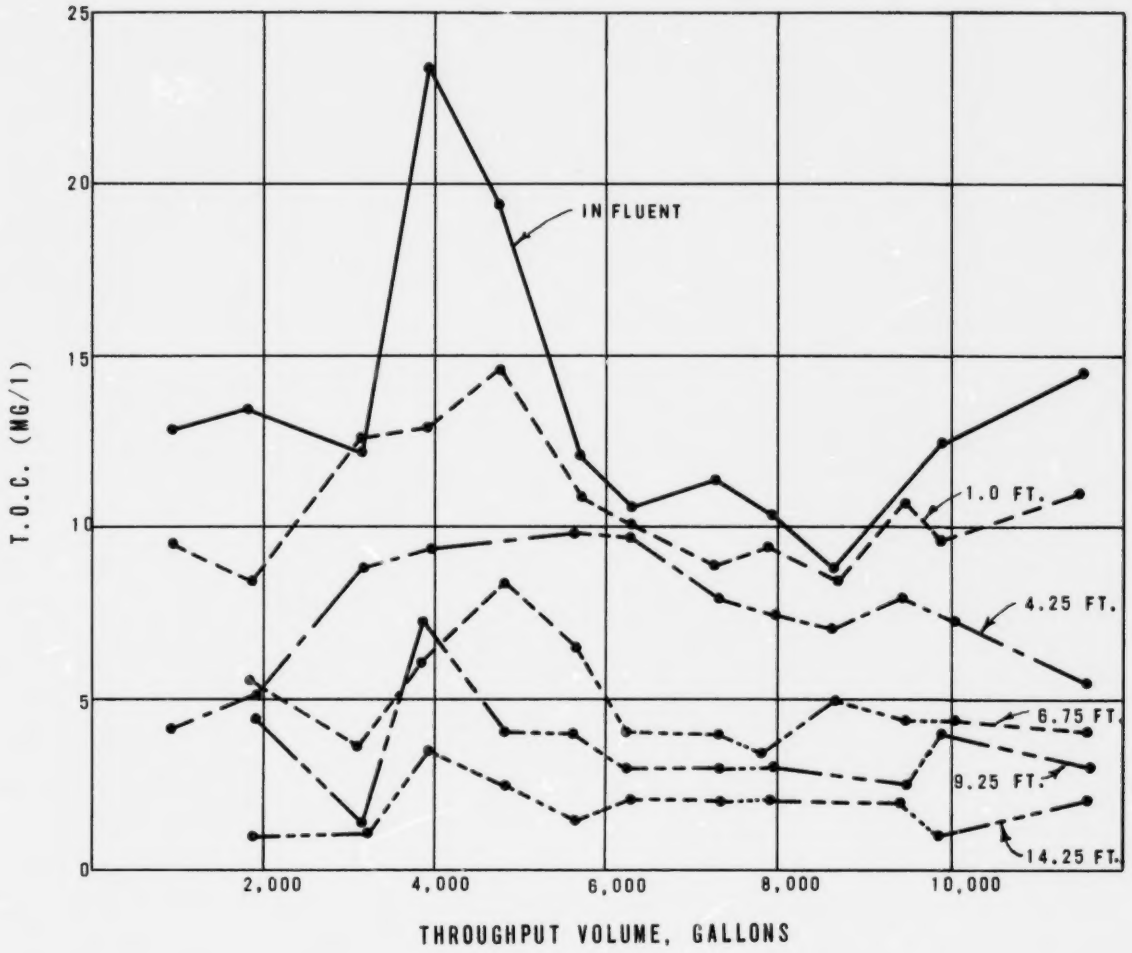

FIGURE 4
T.O.C. (TOTAL ORGANIC CARBON) BREAKTHROUGH CURVE FOR PCC 2
(8X30 MESH CARBON - 4.1 GPM/FT^2)

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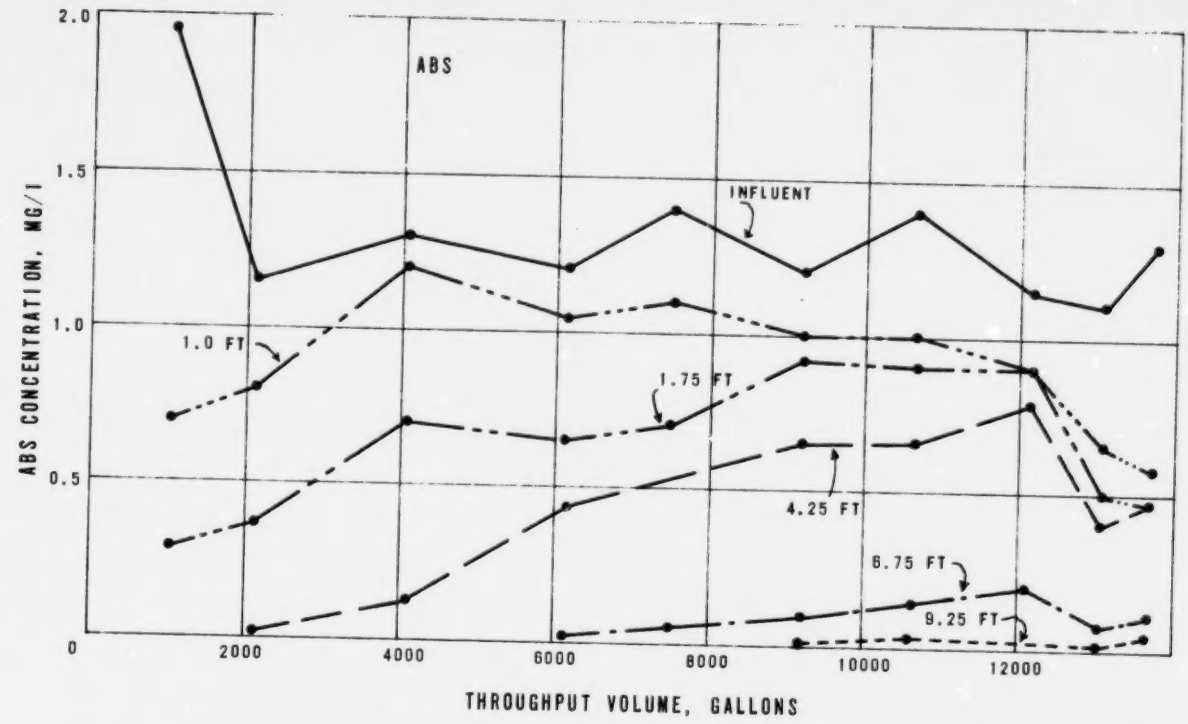

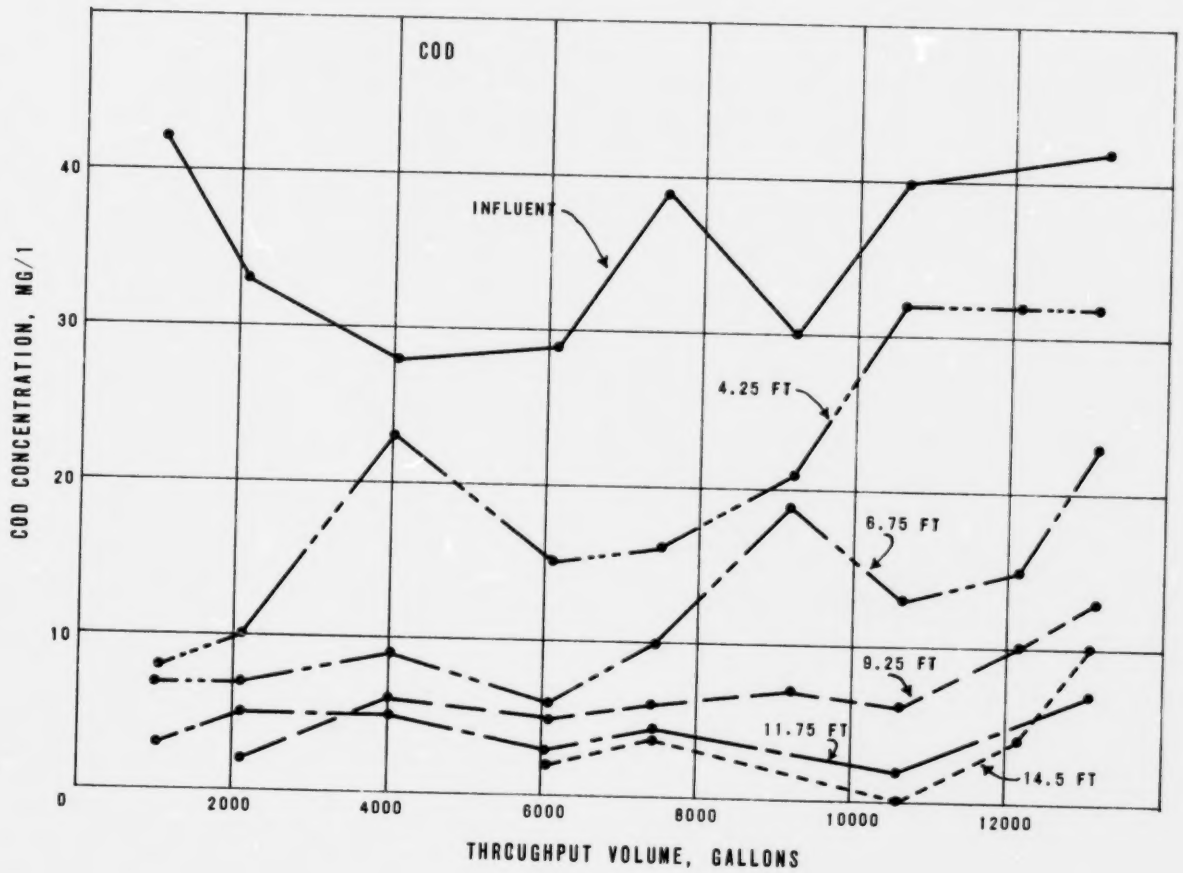

FIGURE 5

ABS AND COD BREAKTHROUGH CURVES FOR PCC 3

(12X40 MESH CARBON - 6.5 GPM/FT^2)

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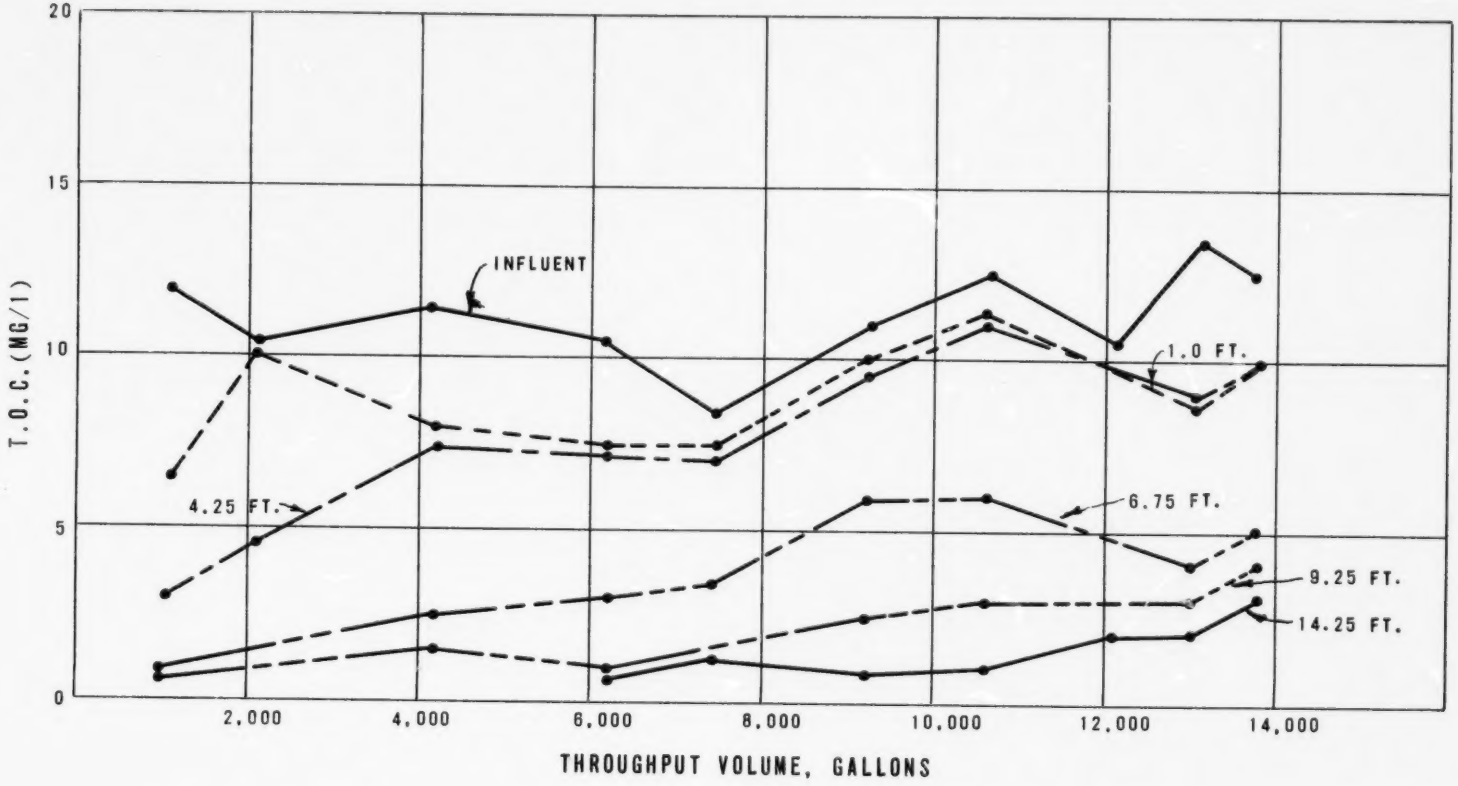
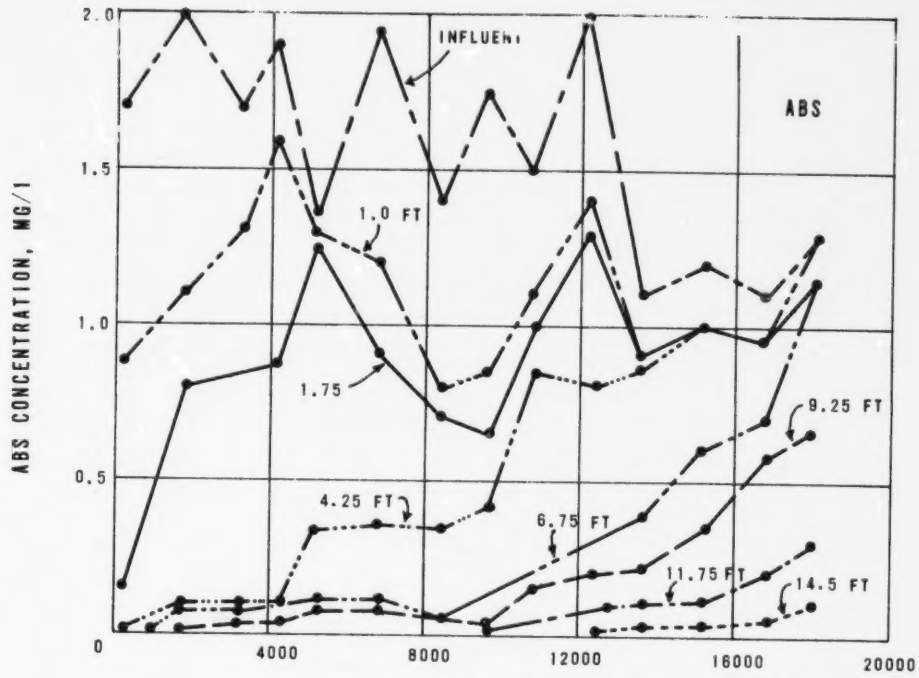


FIGURE 6
T.O.C. (TOTAL ORGANIC CARBON) BREAKTHROUGH CURVE FOR PCC 3
(12X40 MESH CARBON - 6.5 GPM/FT^2)



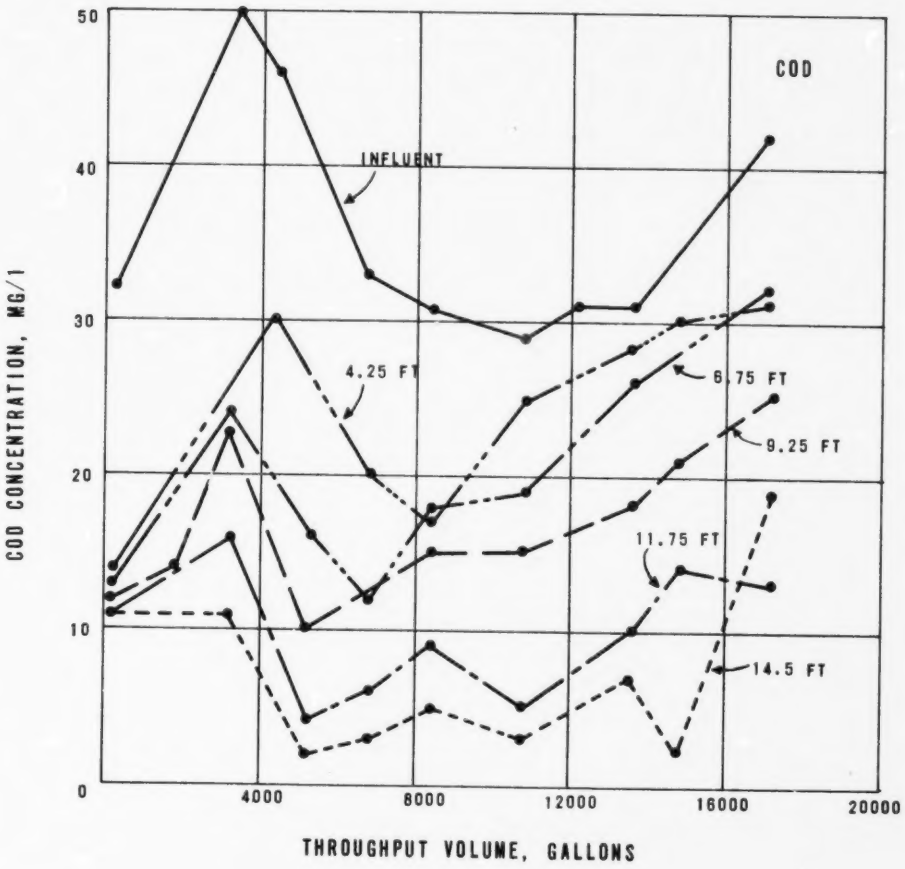


FIGURE 7

ABS AND COD BREAKTHROUGH CURVES FOR PCC 4
(8X30 MESH CARBON - 6.5 GPM/FT^2)

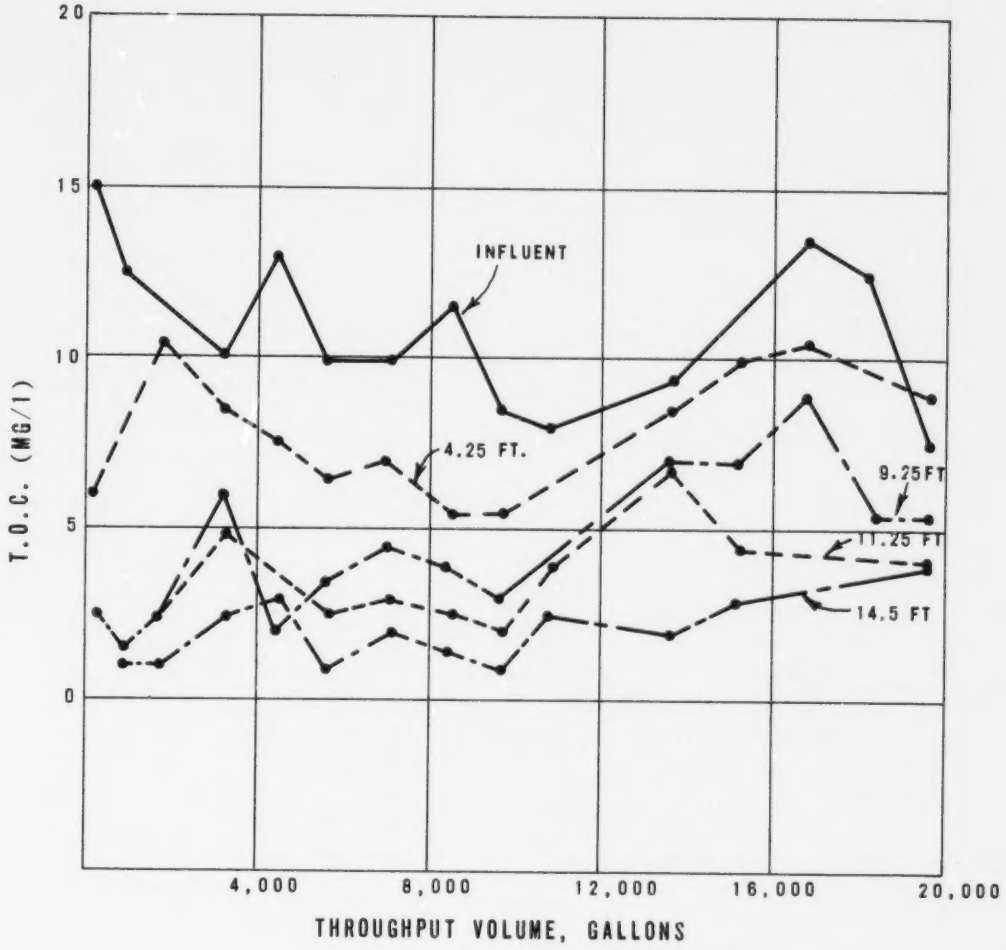


FIGURE 8
T.O.C. (TOTAL ORGANIC CARBON) BREAKTHROUGH CURVE FOR PCC 4
(8X30 MESH - 6.5 GPM/FT^2)

C3520.5

TABLE 2

CARBON COLUMN OPERATING DATA - RUN ONE

COLUMN	CARBON (1)	AVG SURFACE LOADING RATE GPM/FT^2	AVG. RESIDENCE TIME, MINUTES	VOL. PASSED, GALLONS	BED VOLUMES PASSED	APPLIED LOADING			AVG INFLUENT CONC, MG/L			EFFLUENT CONC. AT END OF RUN, MG/L		
						LBS ABS	LBS COD	LBS TOC	ABS	COD	TOC	ABS	COD	TOC
PCC 1	VIRGIN 8X30	4.5	24.2	12752	1372	0.142	3.58	1.49	1.34	33.6	11.7	.002	2.5	2.0
PCC 2	VIRGIN 8X30	4.1	26.4	9967	1070	0.137	3.18	1.25	1.65	38.3	11.0	.002	1.5	1.0
PCC 3	WASHED VIRGIN 12X40	6.5	16.7	13138	1415	0.158	3.56	1.23	1.44	32.7	10.7	.003	10	3.0
PCC 4	WASHED VIRGIN 8X30	6.5	16.7	18226	1970	0.218	5.45	1.80	1.43	35.9	11.0	.12	5	4.0
MAIN COLUMNS	VIRGIN 8X30	7.6	13.7	55.3X10^6	2040	759.5	16,055	5,797	1.65	35.0	12.6	0.5	26	7.0

(1) ALL CARBON IS PITTSBURGH ACTIVATED CARBON CO., TYPE SGL.

C3520.5

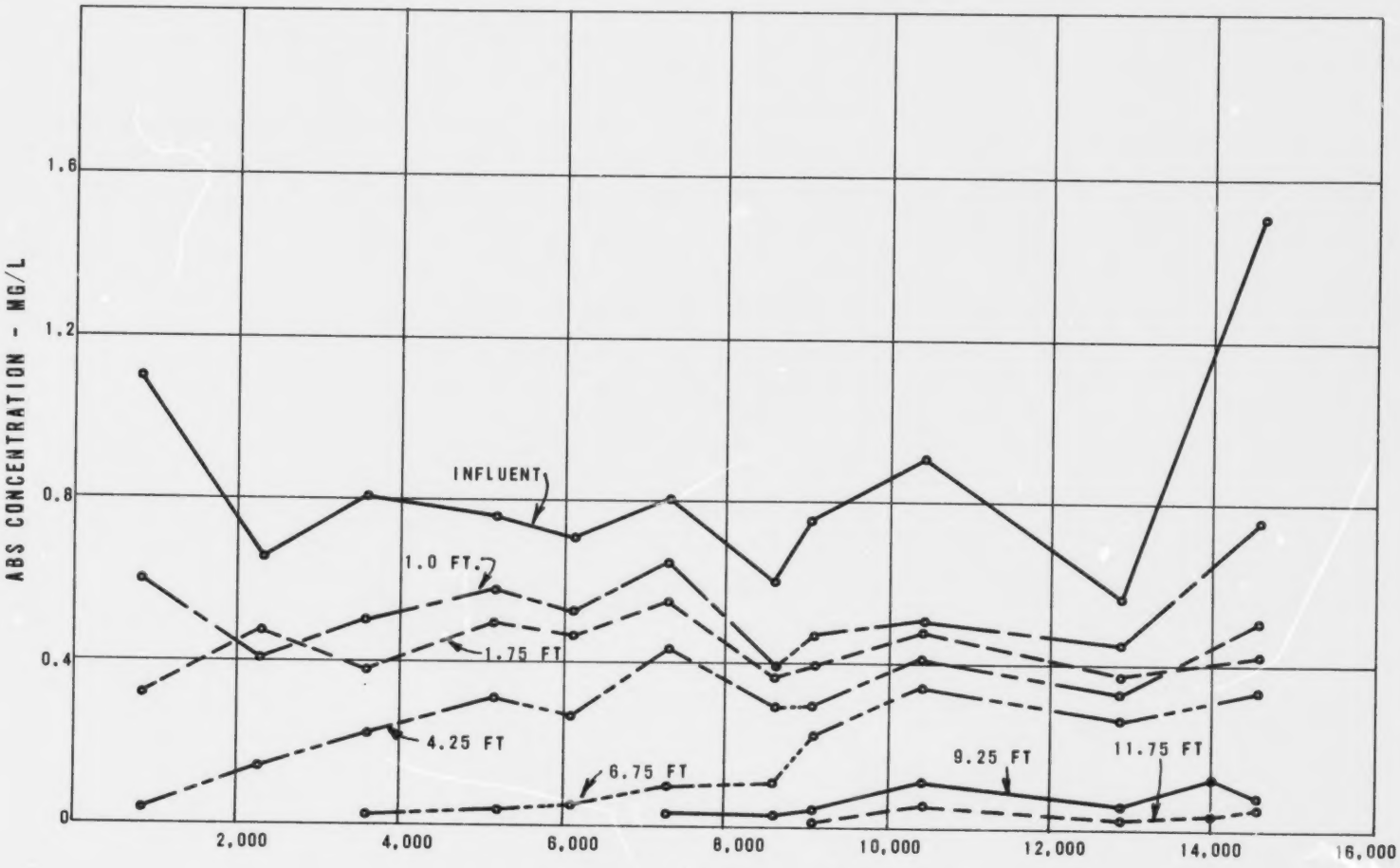


FIGURE 9

ABS BREAKTHROUGH CURVE

PCC 5

(30 LBS. 8X30 MESH VIRGIN CARBON - 4.6 GPM/FT^2)

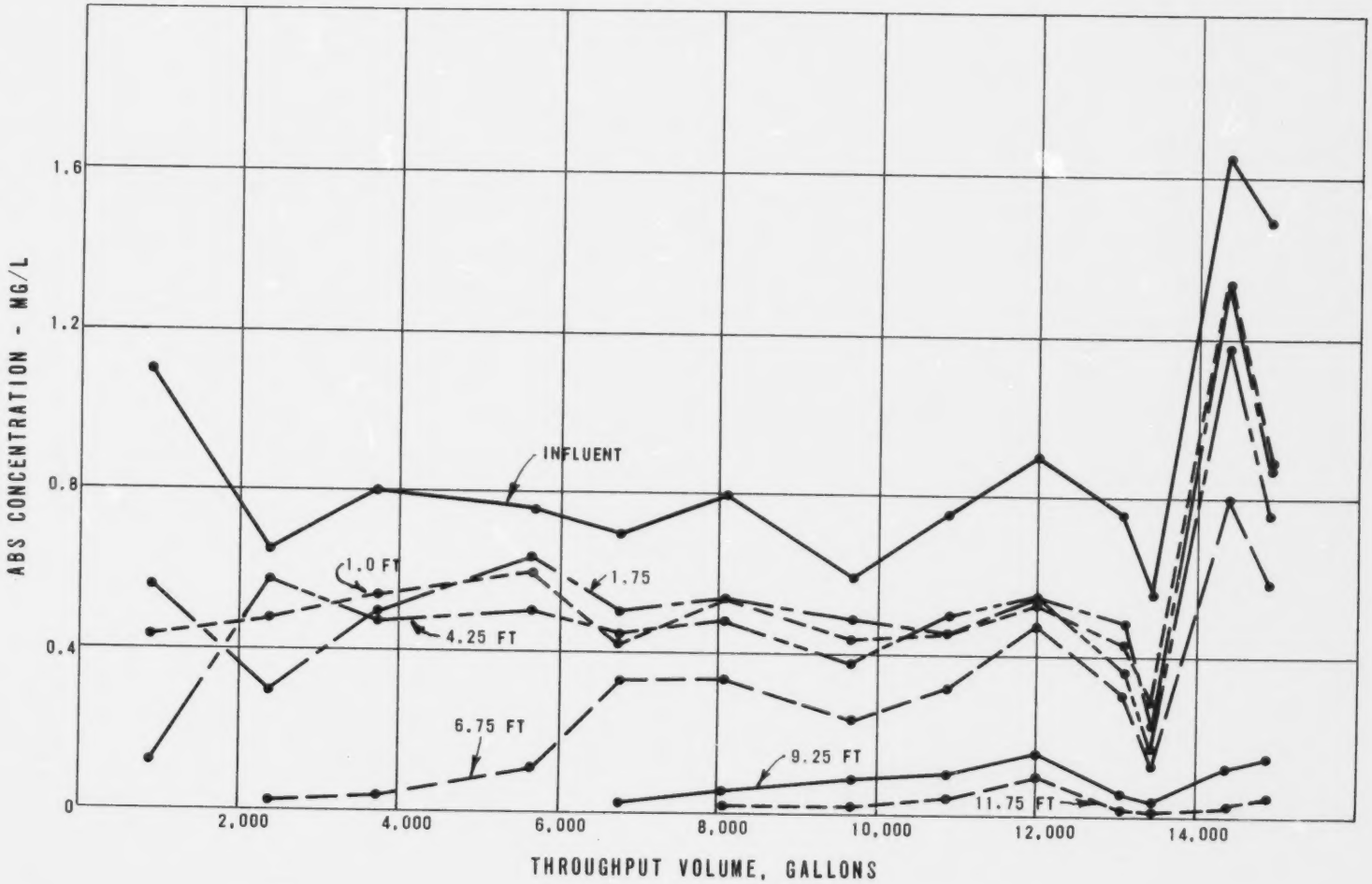


FIGURE 10

ABS BREAKTHROUGH CURVE

PCC 6

(30 LBS. 8X30 MESH 1ST CYCLE REGENERATED CARBON - 4.6 GPM/FT^2)

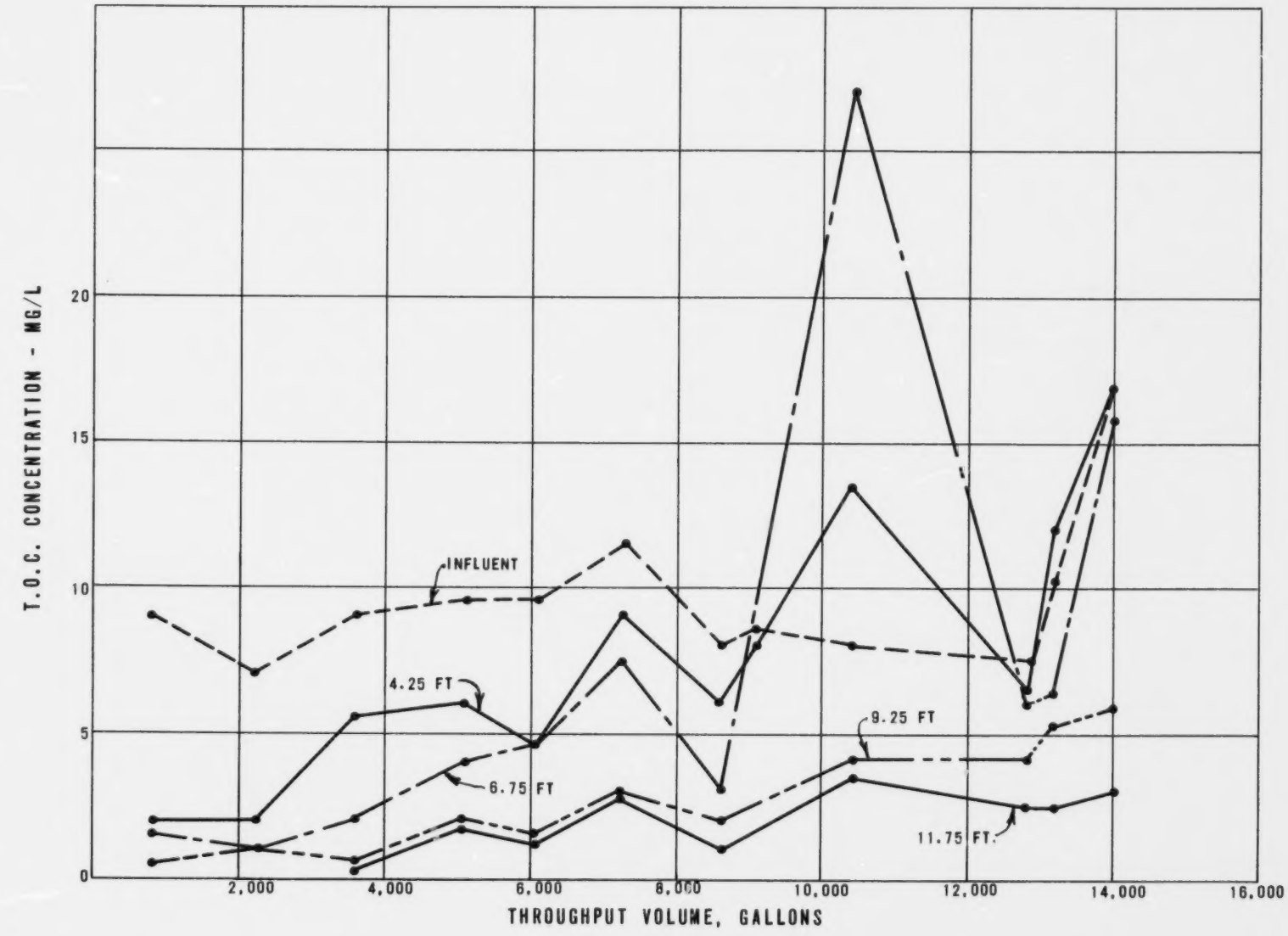


FIGURE 11

T.O.C. BREAKTHROUGH CURVE

PCC 5

(30 LBS. 8X30 MESH VIRGIN CARBON - 4.6 GPM/FT^2)

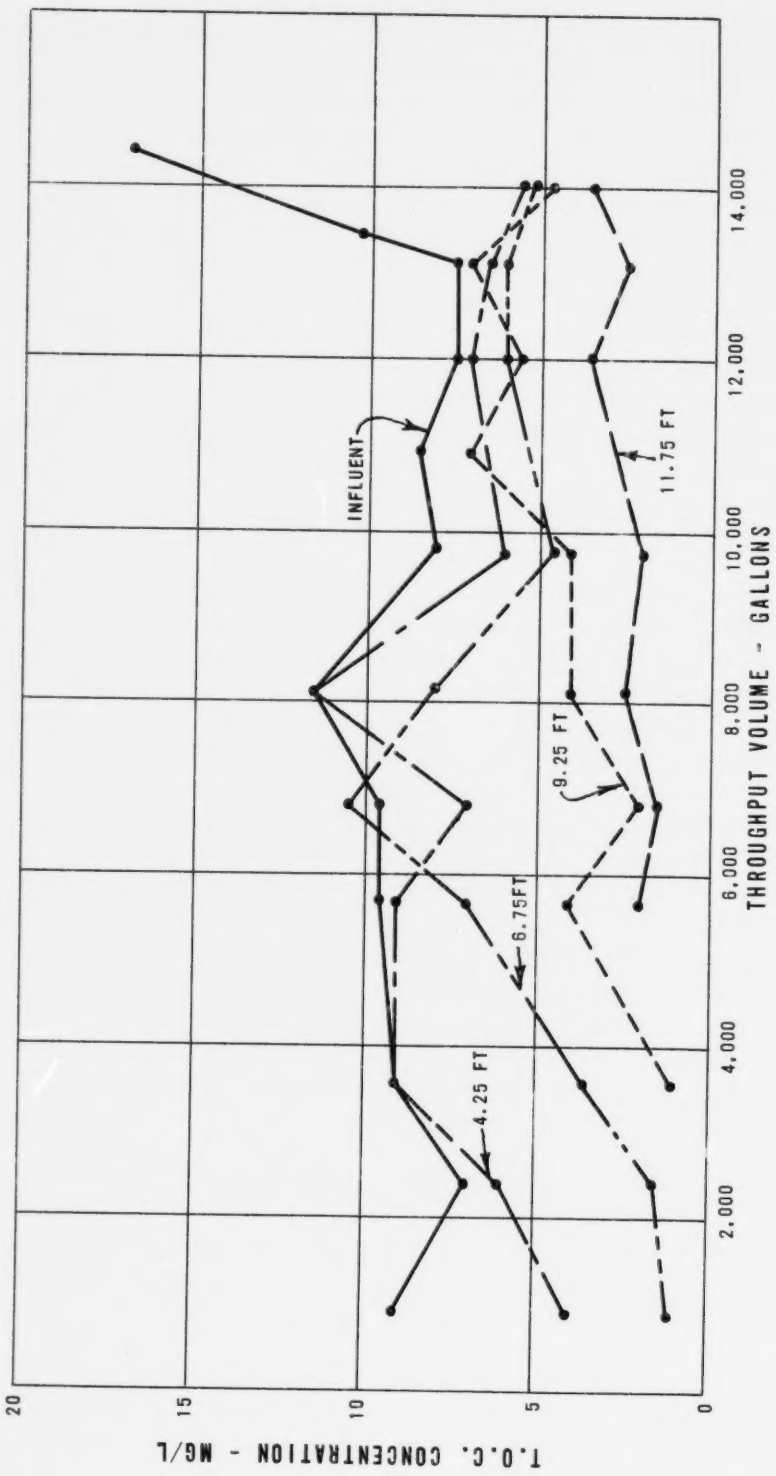


FIGURE 12

T.O.C. BREAKTHROUGH CURVE

PCC 6

(30 LBS. 8X30 MESH 1ST CYCLE REGENERATED CARBON - 4.6 GPM/FT^2)

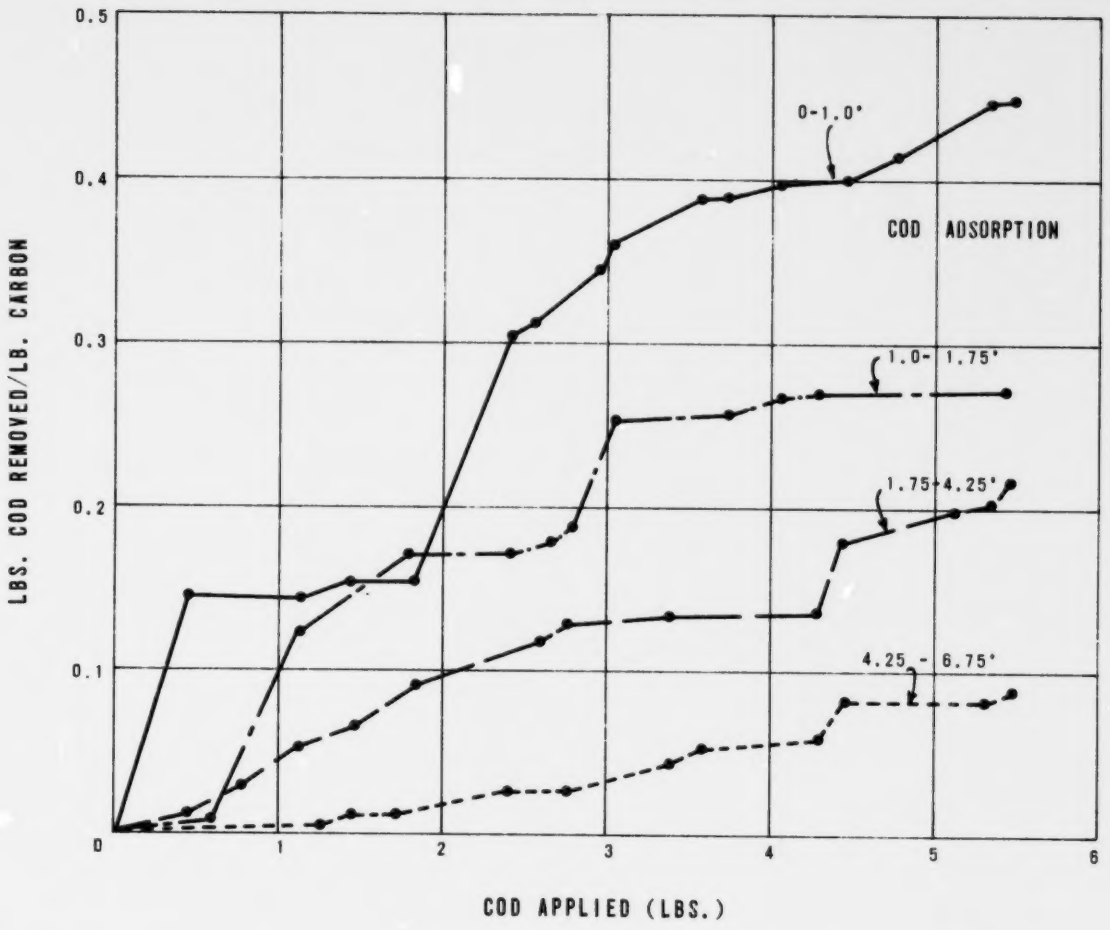
Figure 13 shows that the first foot of carbon continued to adsorb ABS and COD at a more rapid rate than the increment of carbon immediately above the first foot of carbon which had essentially ceased to remove adsorbate, even though this increment had not adsorbed as much material as the lower foot of carbon. This decrease in adsorptive capacity is believed to have been caused by mechanical fouling of the carbon. There are several points on these curves where the rate of adsorption suddenly rises in the 0-1.0 foot increment after having reached a plateau. These sudden increases in the rate of adsorption occurred at times when the column was downflushed. This increase in the rate of adsorption and the previously mentioned observations can be attributed to the fact that the carbon was mechanically fouled and that by downflushing the carbon the floc particles coating the carbon granules were removed from a portion of the carbon and that adsorption was again possible. As Figures 13 and 14 show, downflushing did not remove the floc at a depth of 1.75 to 4.25 feet. The floc particles apparently had not fouled the carbon significantly beyond 4.25 feet as the carbon continued to adsorb beyond this point.

Figure 15 shows the ABS profile for PCC 4 after various increments of flow. These profiles also reflect the effect of mechanical fouling. Although the lowest portion of the column continued to reduce the influent concentration, Co, the concentration, after 13,560 gallons had passed, was not reduced further by the next segment of carbon. The ABS concentration was then reduced as the water reached the carbon which was not fouled.

Efficiency of Main Carbon Columns. Figures 16 and 17 show the breakthrough curves for ABS, COD, and TOC on the main carbon columns and the associated carbon dose when the minimum effluent water quality standards were attained. To date, approximately 112 million gallons of separation bed effluent have been passed through the carbon columns at an average carbon dose of 740 pounds per million gallons and at an average residence time of 15.4 minutes. This dose probably could have been reduced if it had not been necessary at the first removal of spent carbon to remove partially spent carbon in order to correct problems of excessive head loss.

As shown on Figure 16, the carbon dose was reduced to 390 pounds per million gallons on the last carbon cycle. During this cycle the residence time averaged about 20 minutes due to the low winter flows experienced at the South Tahoe PUD plant. The longer residence time is felt to be the prime factor contributing to the lower carbon dose.

The principle underlying the countercurrent operation of the carbon columns is clearly demonstrated by the data shown on Figures 13 and 14 and Table 3. It is evident that the bulk of the adsorption is taking place in the first foot of the carbon column. By operating the column in a countercurrent manner, only the most saturated carbon will be withdrawn for regeneration.



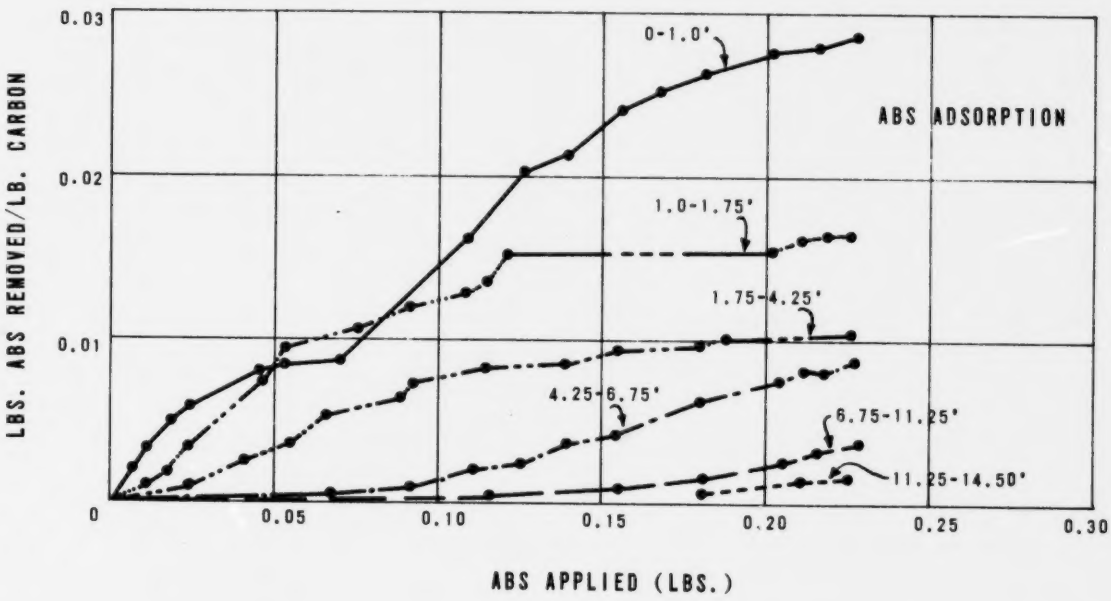


FIGURE 13

COD AND ABS ADSORPTION PILOT CARBON COLUMN 4

(VIRGIN 8X30 MESH CARBON

6.5 GPM/FT^2)

C3520.5

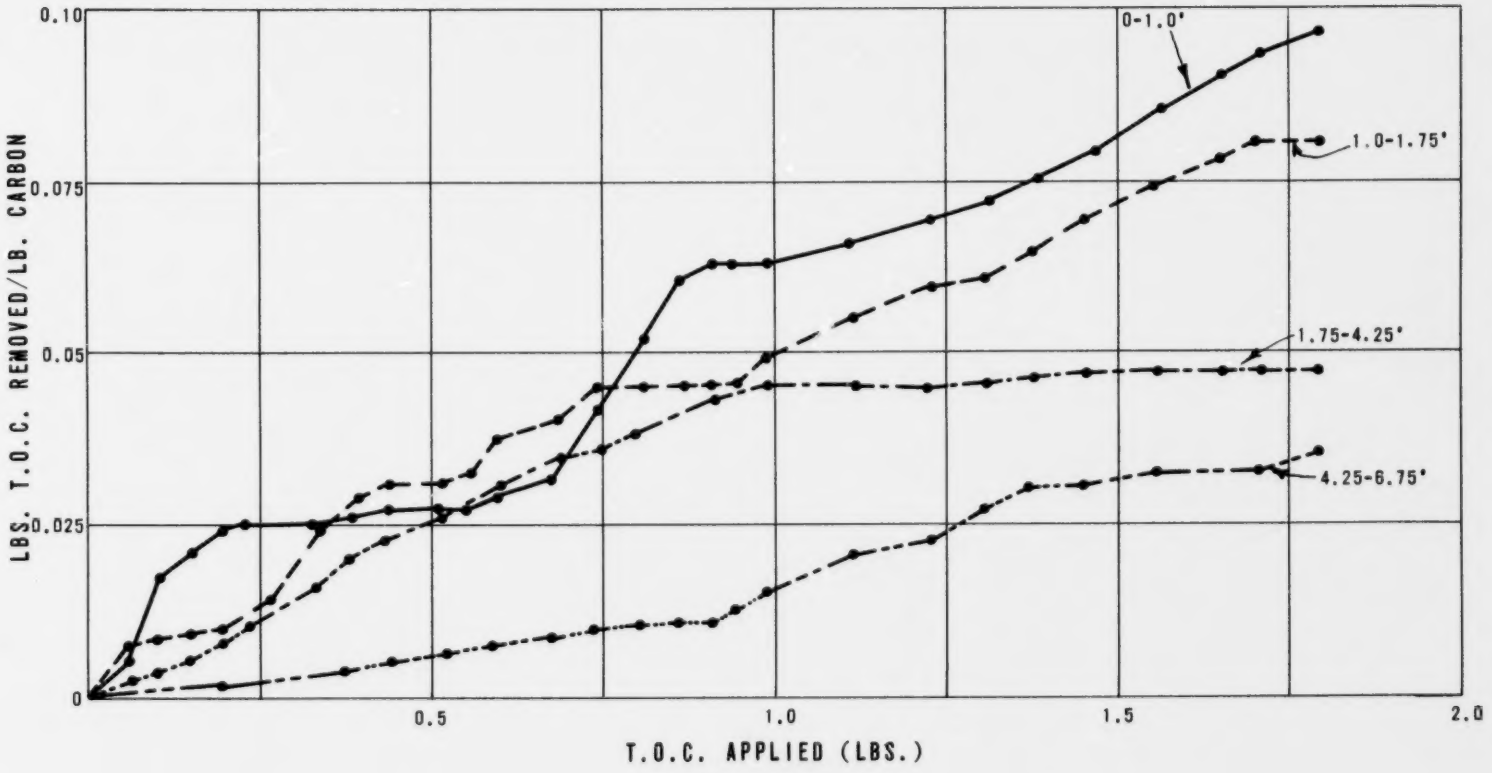


FIGURE 14
T.O.C. ADSORPTION
PCC 4

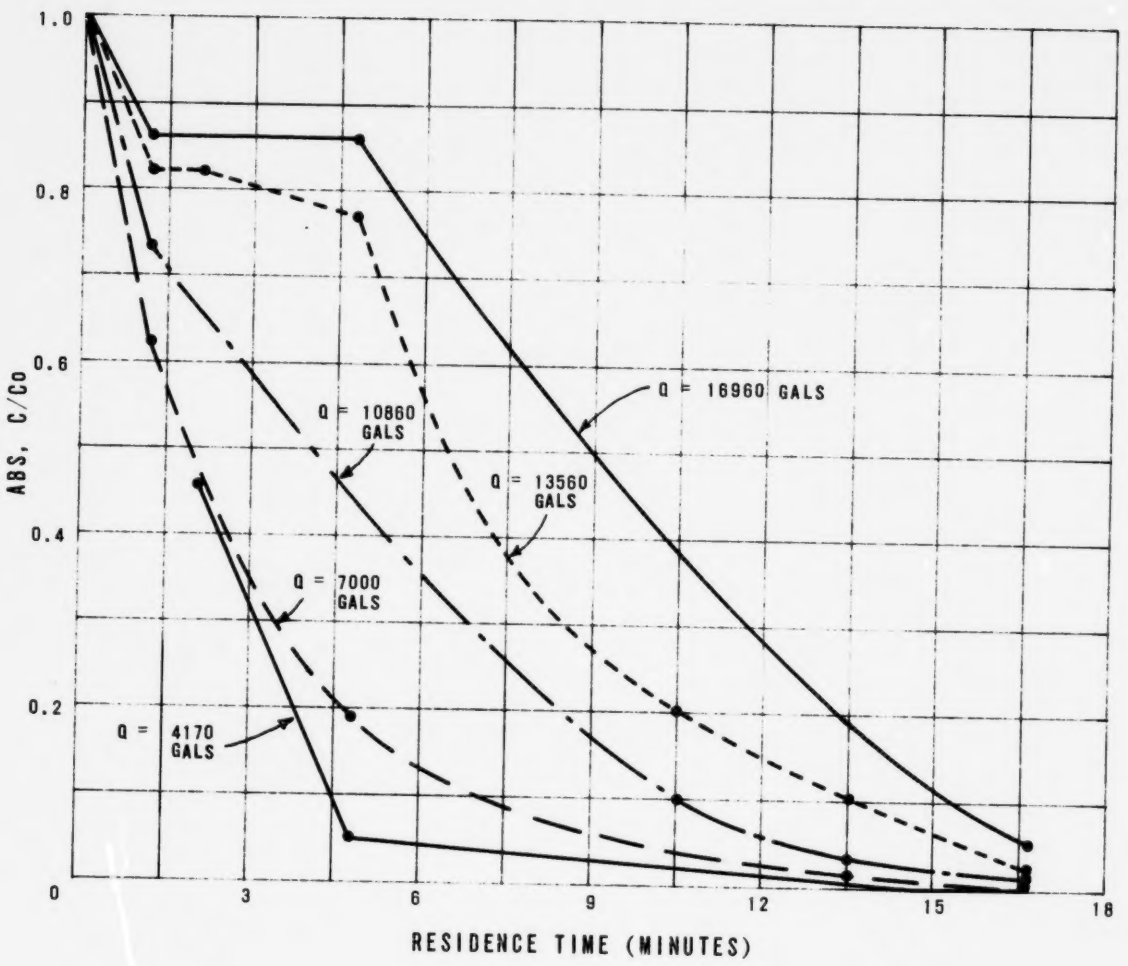


FIGURE 15

ABS ADSORPTION PROFILE FOR VARIOUS FLOWS, PCC 4

VIRGIN 8X30 MESH CARBON, 6.5 GPM/FT^2

C3520.5

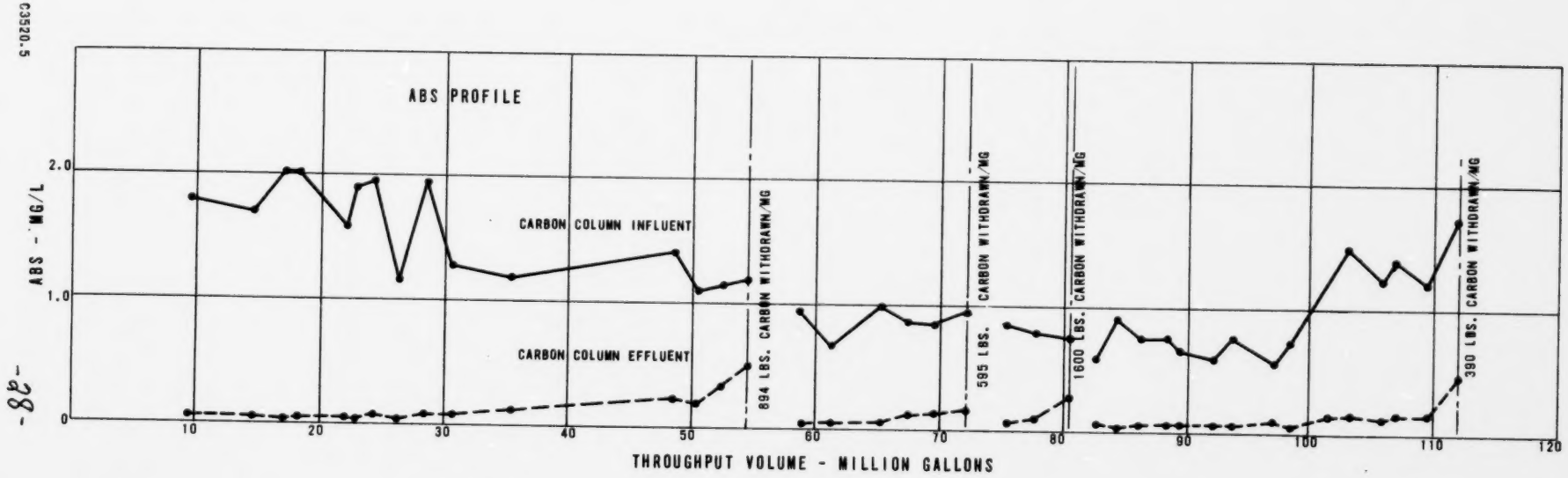
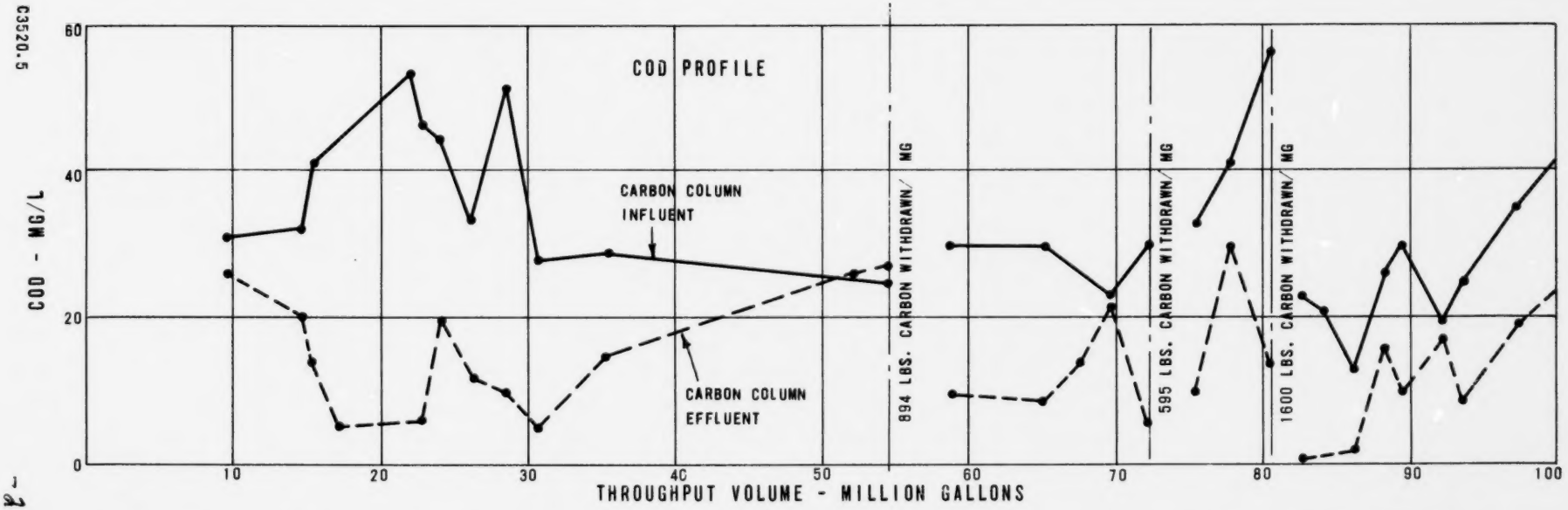


FIGURE 16
MAIN CARBON COLUMN OPERATING DATA

C3520.5



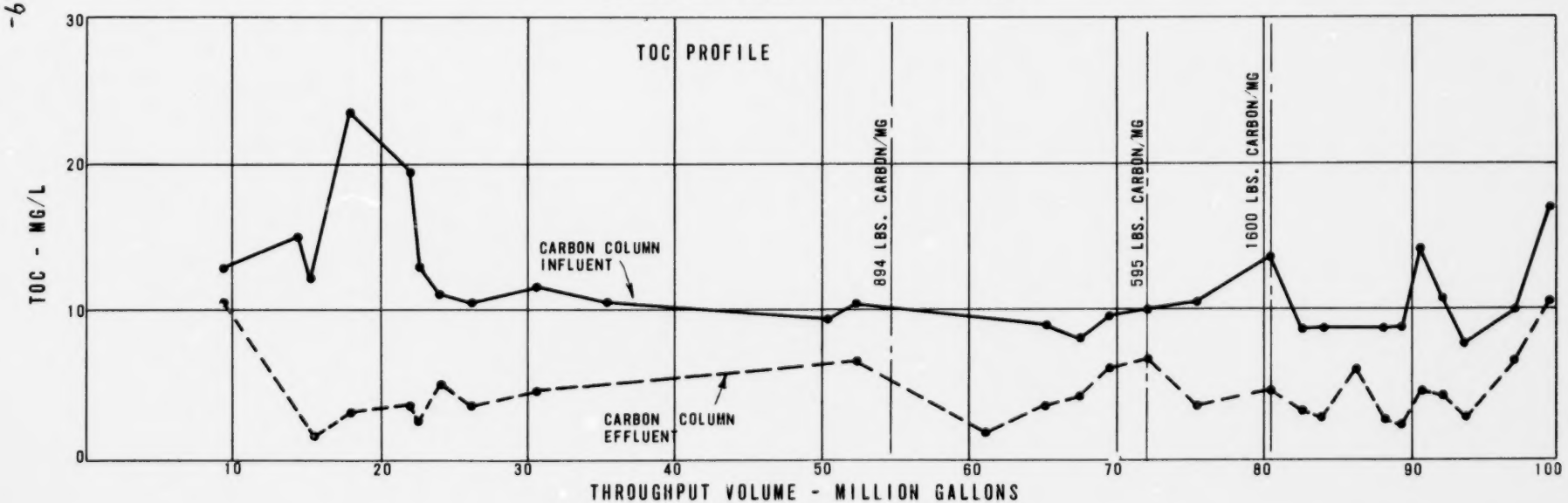


FIGURE 17

MAIN CARBON COLUMN OPERATING DATA

Based upon data from PCC 4, the bottom one foot of carbon had adsorbed 2.8 percent ABS by weight and 45 percent COD by weight prior to the first withdrawal. Due to the mechanical fouling discussed earlier, carbon at higher levels in the column was no longer adsorbing organic materials, although it was not saturated to the same degree as the bottom one foot of carbon. Because of this fouling, the carbon withdrawn for the first regeneration, although no longer adsorbing at a significant rate, averaged only 0.9 percent ABS adsorption by weight and 17 percent COD adsorption by weight.

TABLE 3

PERCENT SATURATION OF CARBON FOR
INCREMENTS OF DEPTH AT END OF RUN 1 FOR PCC 4

Depth Feet	Lb. COD Removed Lb. Carbon	Lb. ABS Removed Lb. Carbon	Lb. TOC Removed Lb. Carbon	Percent Saturation, Relative to First Foot of Carbon		
				COD	ABS	TOC
0 -1.0	0.448	.0285	.096	100	100	100
1.0 -1.75	0.270	.0163	.082	60.3	57.4	85.5
1.75-4.25	0.218	.0102	.047	48.6	35.9	49.0
4.25-6.75	0.085	.0085	.034	19	29.8	35.0
6.75-11.25	---	.0035	---	---	12.3	---
11.25-14.50	---	.0015	---	---	5.4	---

Table 4 shows the quantities of ABS, COD, and TOC removed by the pilot carbon columns. The carbon columns removed 98 percent of the applied ABS and approximately 80 percent of the applied organic loading.

The carbon dose required to obtain the minimum effluent water quality standards is dependent not only on the efficiency of the carbon, but on the volumetric efficiency of the carbon columns. The volumetric efficiency is dependent upon a uniform distribution of flow throughout the carbon bed and a uniform withdrawal of spent carbon from the column.

To determine if a uniform distribution of flow was being obtained, a comparison of the breakthrough curves for the main columns and PCC 4 was made. A comparison of the effluent quality at a residence time of 13.5 minutes for the main carbon columns and PCC 4 is shown on Figure 18 and Table 5. The correlation between the two columns is within experimental error and it can be concluded that a uniform distribution of flow is being achieved in the main carbon columns.

TABLE 4

QUANTITIES OF ABS, COD, TOC REMOVED

Pilot Carbon Column	ABS			COD			TOC		
	Lbs. Applied	Lbs. Removed	Percent Removed	Lbs. Applied	Lbs. Removed	Percent Removed	Lbs. Applied	Lbs. Removed	Percent Removed
1	.1517	.1494	98.5	3.575	3.078	86	1.4920	1.2145	81.5
2	.1560	.1521	98	3.1750	2.738	86	1.2516	1.0597	84.5
3	.1643	.1632	99.5	3.558	2.843	80	1.2313	0.9824	79.5
4	.2264	.2224	98.5	5.446	4.186	77	1.7989	1.3636	76.0

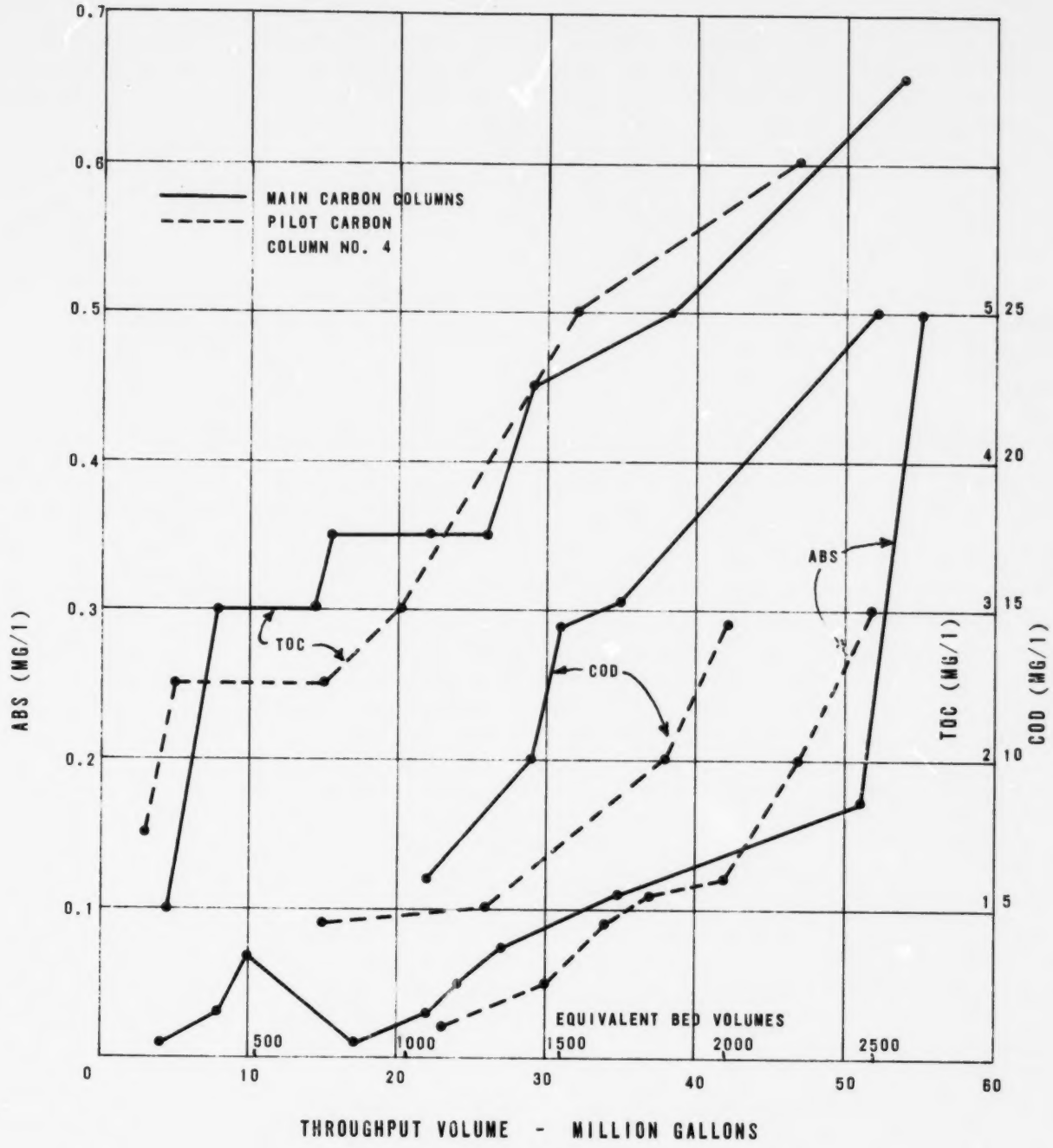


FIGURE 18

COMPARISON OF EFFLUENT QUALITY
AT 13.5 MINUTE RESIDENCE TIME
PCC 4 AND MAIN CARBON COLUMNS

C3520.5

TABLE 5

COMPARISON OF EFFLUENT QUALITY
AT 13.5 MINUTES RESIDENCE TIME
AFTER 2,000 BED VOLUMES

	Full Scale Carbon Columns*	Pilot Carbon Column No. 4*
TOC, mg/l	5.4	5.7
ABS, mg/l	0.14	0.12
COD, mg/l	18	14

*Virgin 8 x 30 SGL Pittsburgh Carbon

It was intended to withdraw carbon from PCC 4 in direct proportion to that withdrawn from the main carbon columns and to continue operating PCC 4 in parallel to the main carbon columns in order to determine if a uniform withdrawal of spent carbon is being obtained in the main carbon columns. However, the head loss across PCC 4 became so excessive that it was impossible to pass a significant volume of water through this column. Attempts to clean PCC 4 by backflushing were futile and this use of the column was abandoned. The volumetric efficiency of the main carbon columns will now be determined by comparing the decrease in efficiency of the regenerated carbon and the corresponding increase in carbon dose in the main columns.

Effect of Flow Rate on Adsorption. PCC 2 and 4 were operated at surface loading rates of 4.1 and 6.5 gpm/ft^2 respectively. Figure 19 is a plot of the ratio of effluent ABS, C, to influent ABS, Co, as a function of residence time. The residence time was calculated using the empty volume of the carbon column. Figure 19 shows that flow rate has no significant affect on ABS adsorption by activated carbon. Figure 20 shows that flow rate did not significantly affect the adsorption of COD.

For the carbon system studied, flow rate, within the range of 4 to 6.5 gpm/ft^2, did not significantly affect the capacity of the carbon. This conclusion is in agreement with the findings of Joyce et al [9, 10] who found flow rates in the range of 2.5 to 10 gpm/ft^2 did not affect the performance of the carbon at a given contact time.

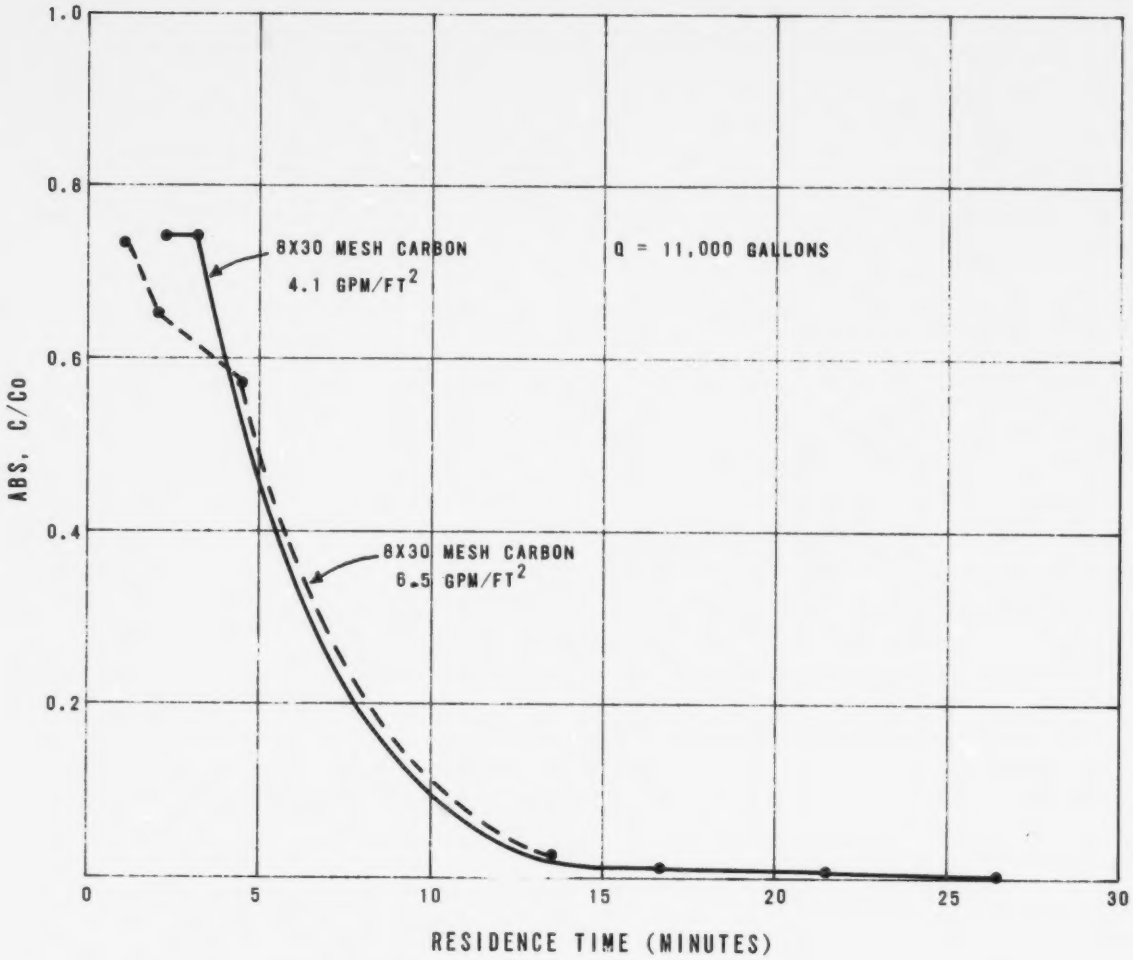


FIGURE 19

EFFECT OF FLOW RATE ON ADSORPTION

C3520.5

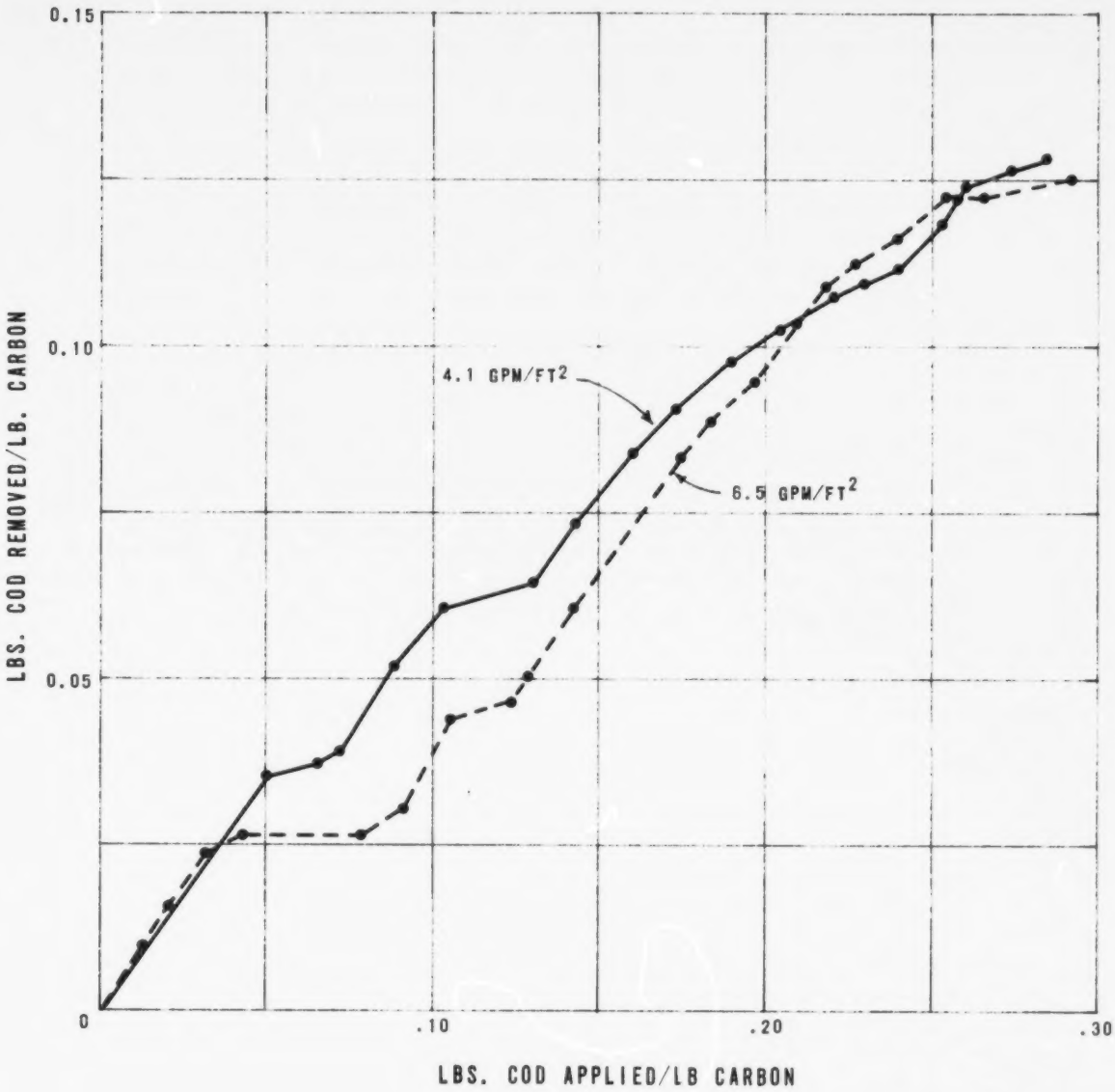


FIGURE 20

COMPARISON OF ADSORPTION OF 8X30 MESH ACTIVATED CARBON

AT A RESIDENCE TIME OF 7.8 MINUTES

AT TWO DIFFERENT FLOW RATES

C3520.5

Effect of Particle Size on Adsorption. Previous studies[8] have shown that the rate of adsorption varies as the inverse square of the diameter of the adsorbent particle. Since carbon particle size primarily affects the rate of adsorption and not the capacity of the carbon, the difference in performance of columns containing different size carbons decreases as the contact time increases [12].

In order to determine the benefit of using a smaller carbon particle size, two pilot carbon columns containing different sizes of carbon were operated in parallel. PCC 3 and 4 were respectively charged with 12 x 40 mesh and 8 x 30 mesh carbon and were operated at a surface loading rate of 6.5 gpm/ft^2.

The breakthrough curves of ABS, COD, and TOC for PCC 3 and 4 (Figures 5 - 8) show that for carbon depths of 6.75 feet and greater, the effluent concentrations of ABS, COD, and TOC are considerably less for the 12 x 40 mesh carbon than for the 8 x 30 mesh carbon. At a throughput volume of approximately 14,000 gallons, the ABS concentration at a carbon depth of 9.25 feet in the 12 x 40 mesh column was 0.05 mg/l. However, a carbon depth of 14.5 feet of the 8 x 30 mesh carbon was required to obtain the same ABS concentration at the same throughput volume.

A comparison of TOC and COD adsorption characteristics of the 12 x 40 and 8 x 30 mesh carbons is shown on Figures 21 and 22. Sufficient adsorption had not occurred above the 9.25-foot level to determine the quantitative difference, if any, in adsorptive capacity at greater carbon depths and longer residence times. It was planned to run PCC 3 (12 x 40 mesh carbon) to obtain data at these longer contact times, but the head loss across this column was so excessive that no water could be passed through the column and the study had to be abandoned.

The study indicates that the 12 x 40 mesh carbon is more efficient in removing ABS, COD, and TOC than is the 8 x 30 mesh carbon for contact times less than 13.5 minutes. At a contact time of 10 minutes (9.25 feet - Figure 21) the 12 x 40 mesh carbon is about 35 percent more efficient than the 8 x 30 mesh carbon. Figure 23 shows a superior profile for the smaller carbon particle size. Future studies should include longer contact times to better evaluate the affect of carbon particle size on adsorption at longer contact times.

As previously discussed, the problem of excessive head loss across the pilot carbon columns could not be corrected. However, it was observed that the problems of excessive fines and physical fouling of the carbon were much more pronounced with the 12 x 40 mesh carbon than the 8 x 30 mesh carbon. Changes in pilot column design should reduce the head loss problem associated with both the 12 x 40 mesh and 8 x 30 mesh carbons in the pilot columns.

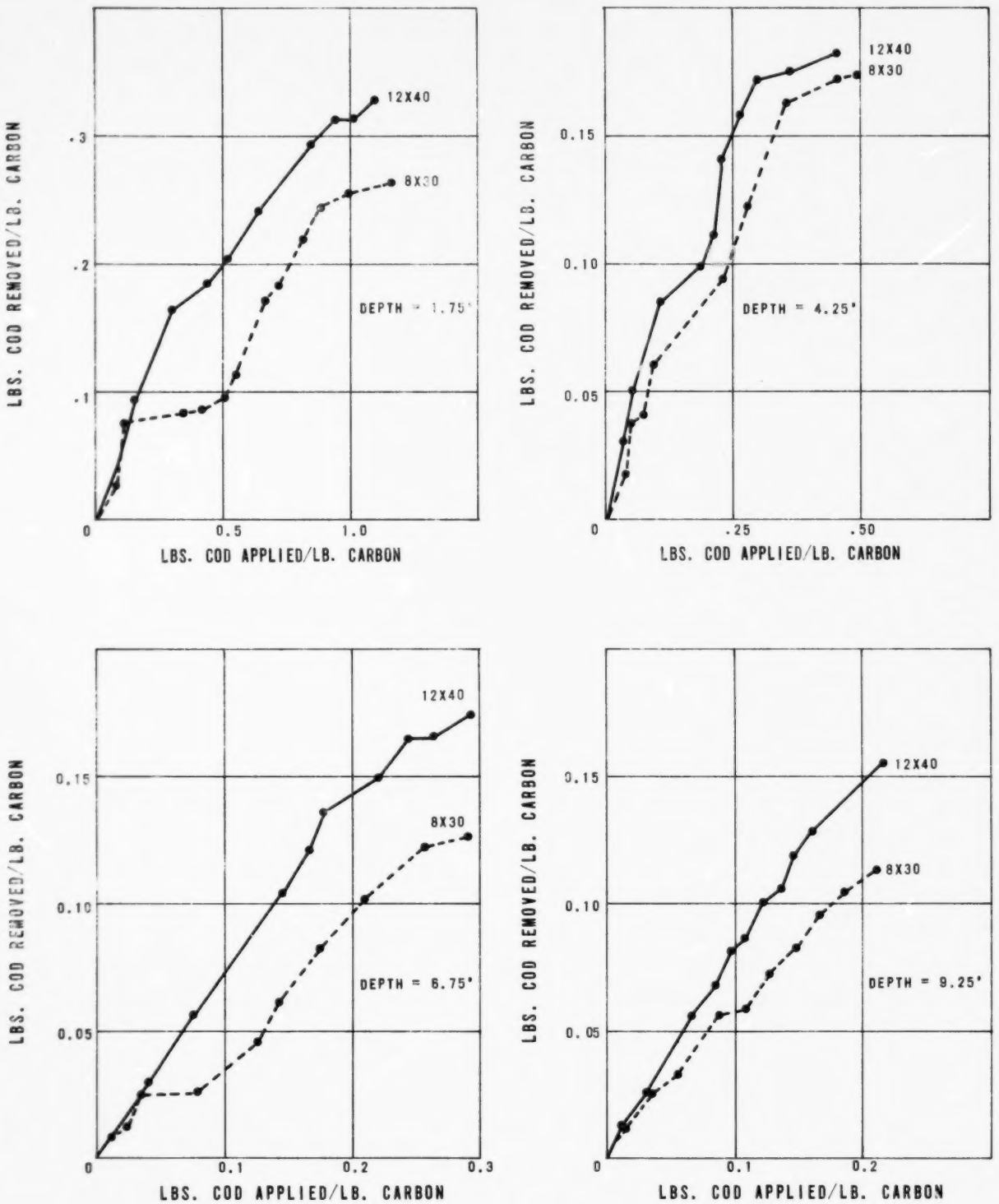


FIGURE 21

COMPARISON OF COD ADSORPTION BY 8X30 AND 12X40 MESH ACTIVATED CARBON

C3520.5

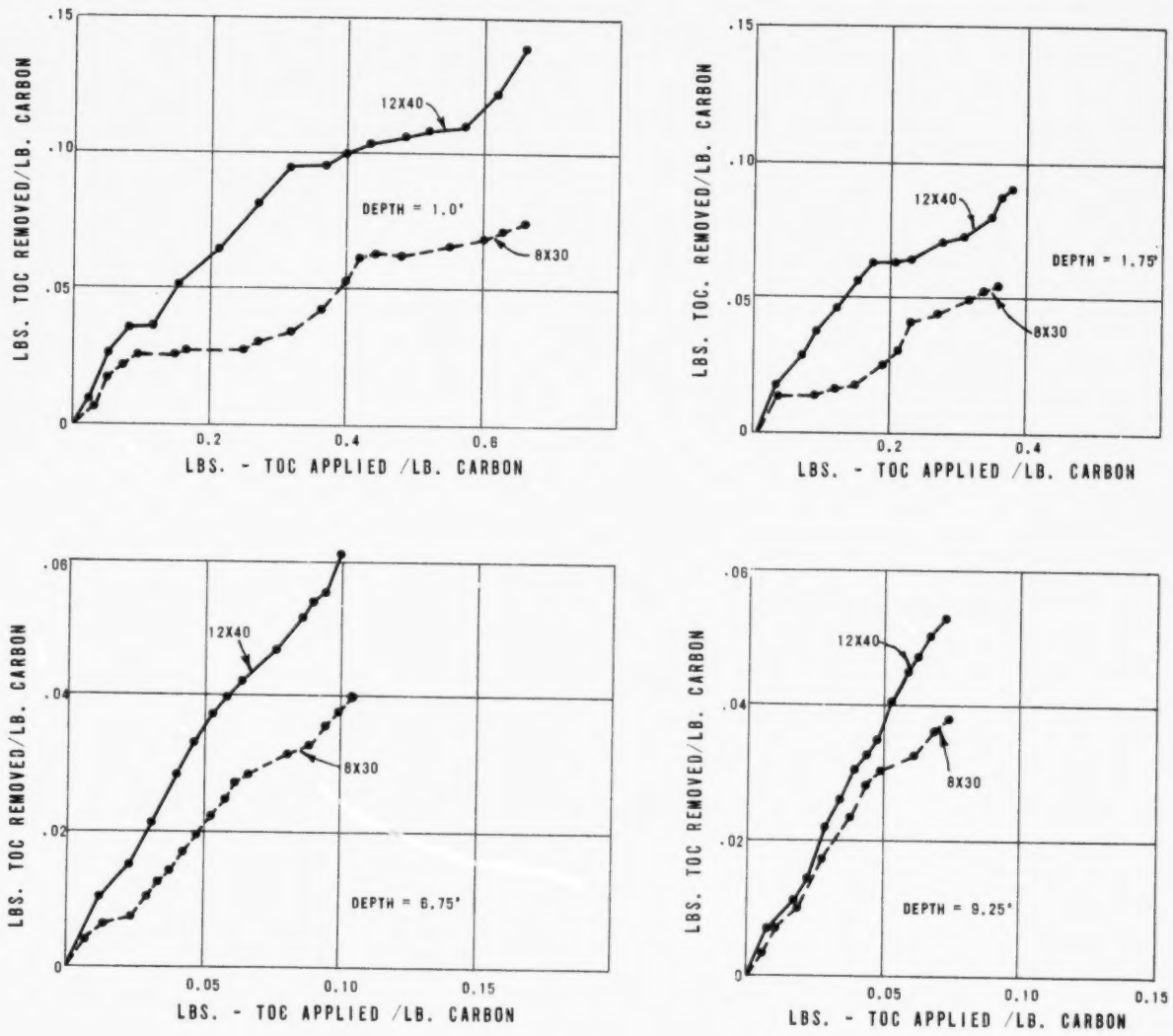


FIGURE 22
COMPARISON OF TOC ADSORPTION
BY 8X30 AND 12X40 MESH
ACTIVATED CARBON

C3520.5

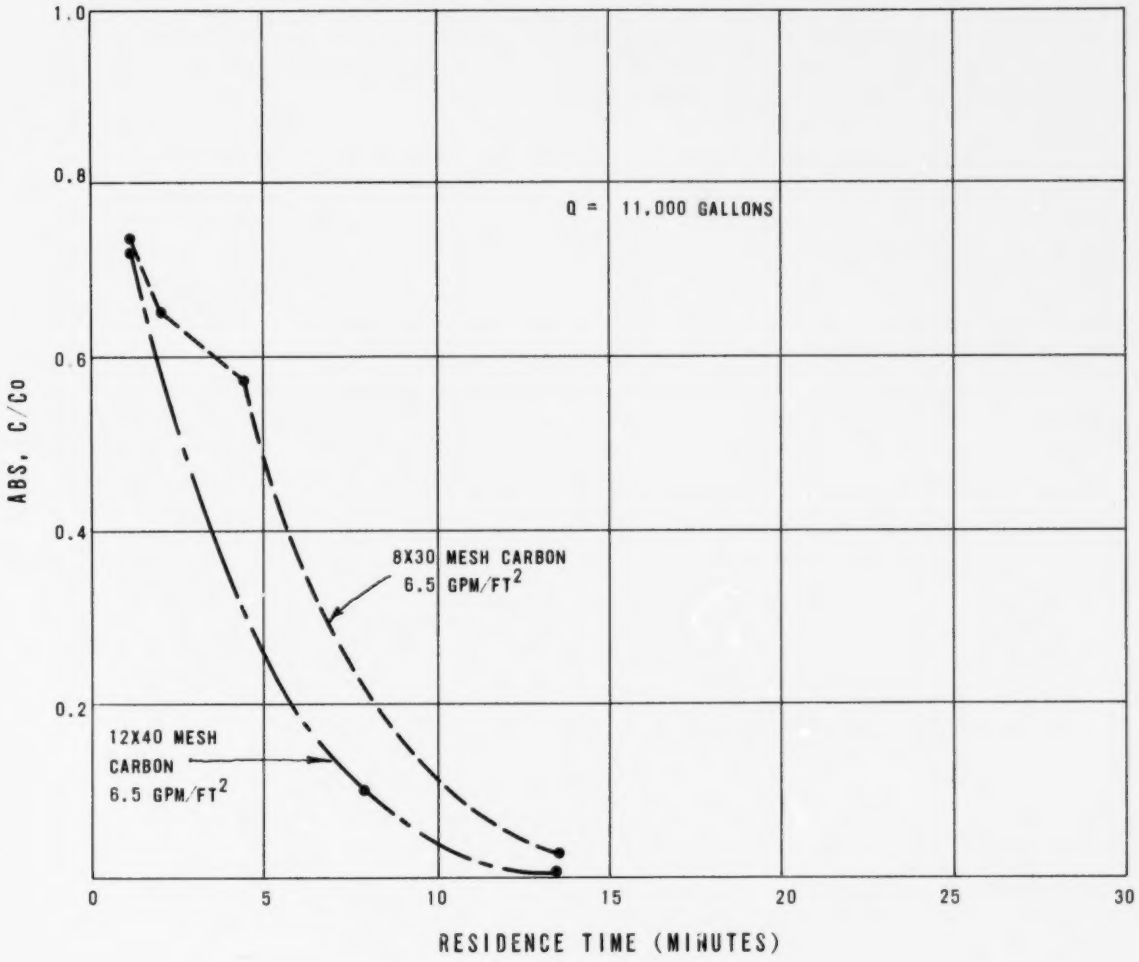


FIGURE 23

EFFECT OF CARBON PARTICLE SIZE ON ADSORPTION

C3520.5

Efficiency of Regenerated Carbon. Following the first regeneration of carbon, a pilot column of virgin 8 x 30 mesh carbon (PCC 5) was operated in parallel with a column of regenerated 8 x 30 mesh carbon (PCC 6). These columns were operated at a surface loading rate of 4.6 gpm/ft^2. Figures 24 - 26 show a comparison of the virgin and regenerated ABS profiles for carbon depths of 4.25, 6.75, and 9.25 feet. These profiles show that the regenerated carbon is not as efficient in removing ABS as is the virgin carbon.

A mathematical integration of the ABS breakthrough curves for PCC 5 and 6 was performed for carbon depths of 1.75, 4.25, and 6.75 feet. Since the columns were charged with identical quantities of carbon and operated at identical surface loading rates, the results were expressed as pounds of ABS removed versus pounds of ABS applied (Figures 27 - 29). The regenerated carbon can be seen to be less efficient in removing ABS.

Figure 30 indicates that the regenerated carbon is at least 10 percent less efficient in removing ABS than is the virgin carbon for contact times less than 11 minutes. It is anticipated that the carbon requirement in the main columns will increase by at least 10 percent as the main columns become filled with regenerated carbon.

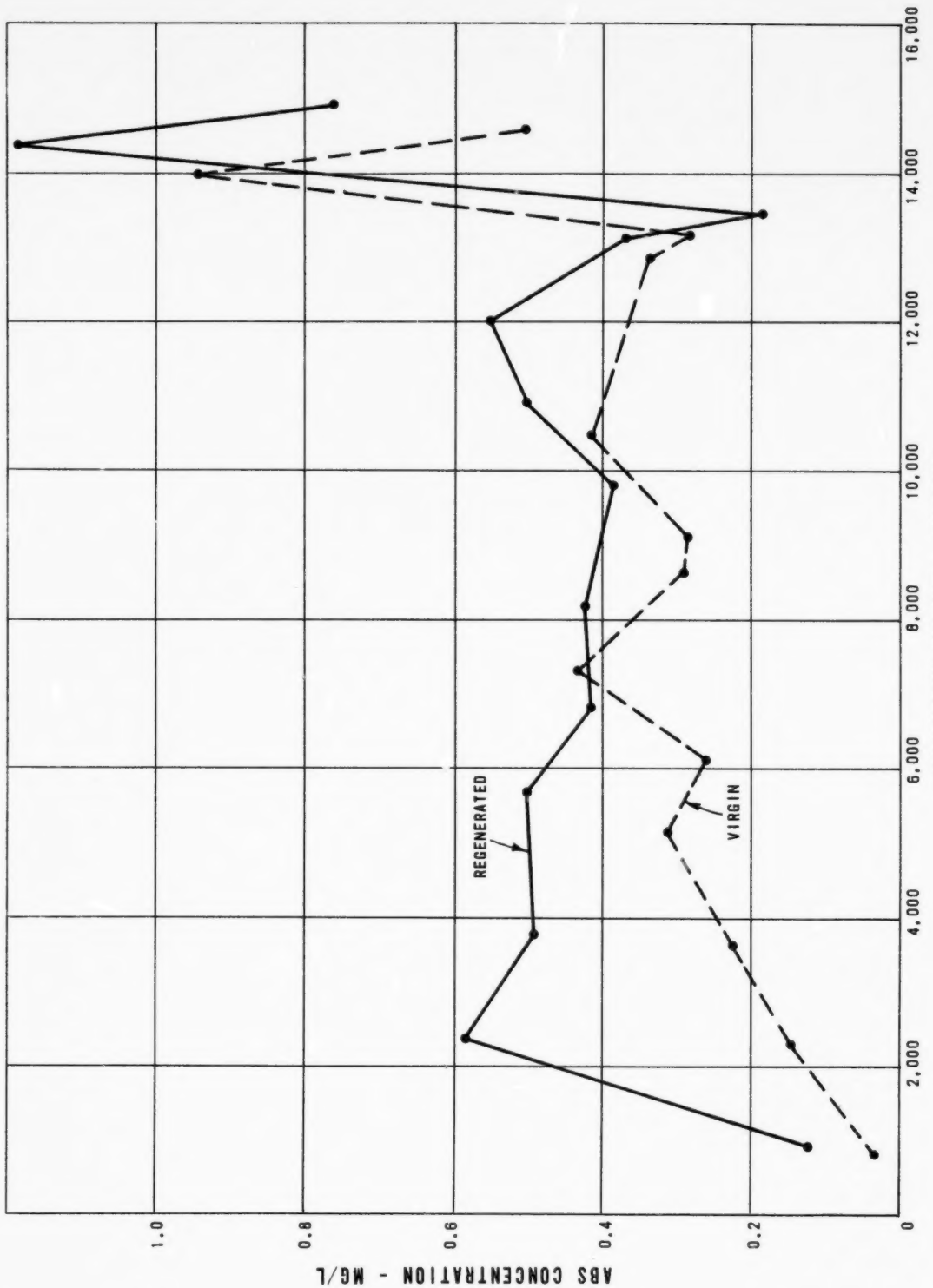


FIGURE 24
COMPARISON OF VIRGIN AND 1st CYCLE REGENERATED CARBON
ABS PROFILE FOR 4.25 FT. CARBON DEPTH

C3520.5

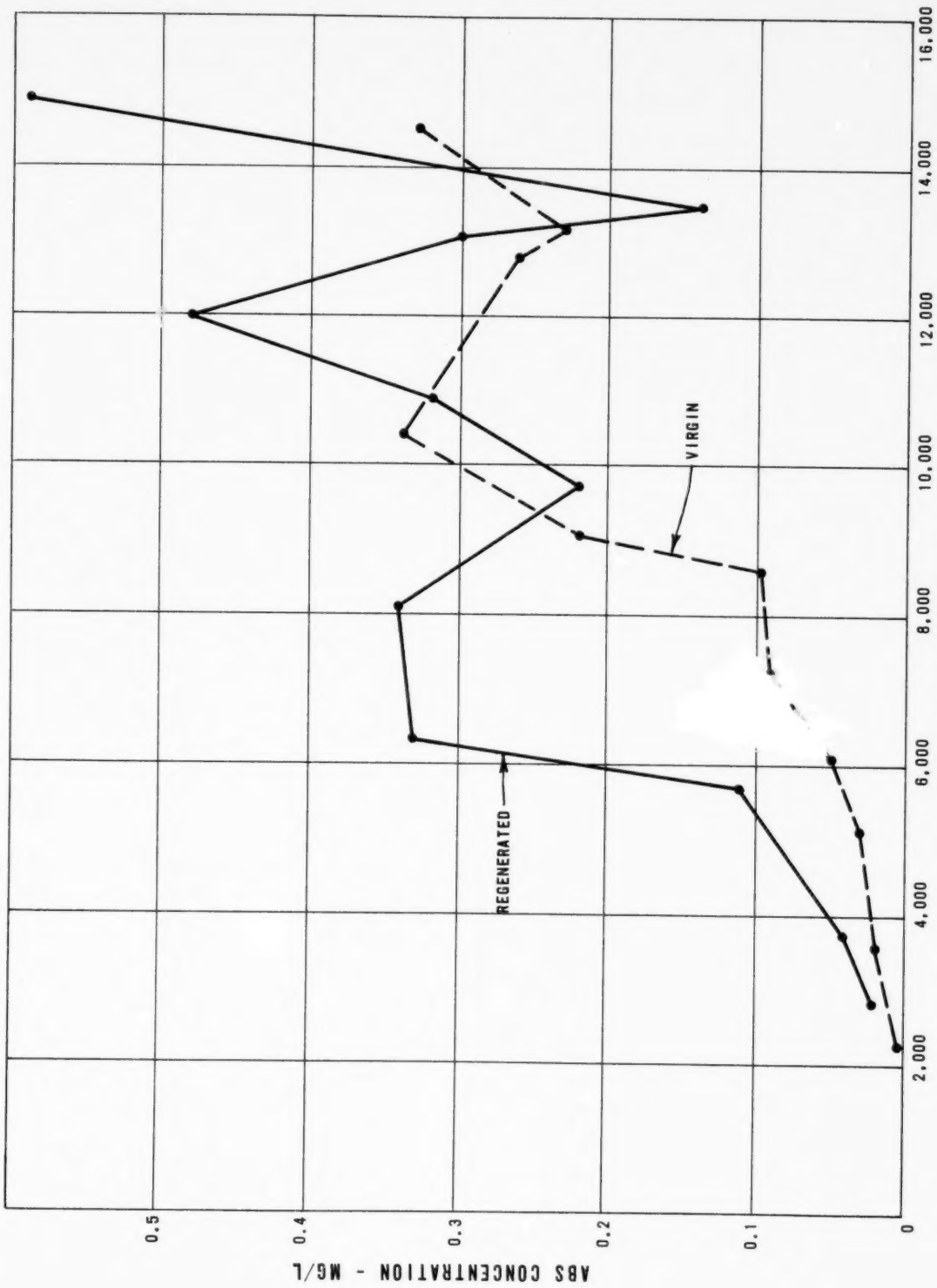


FIGURE 25
COMPARISON OF VIRGIN AND 1ST CYCLE REGENERATED CARBON
ABS PROFILE FOR 6.75 FT. CARBON DEPTH

C3520.5

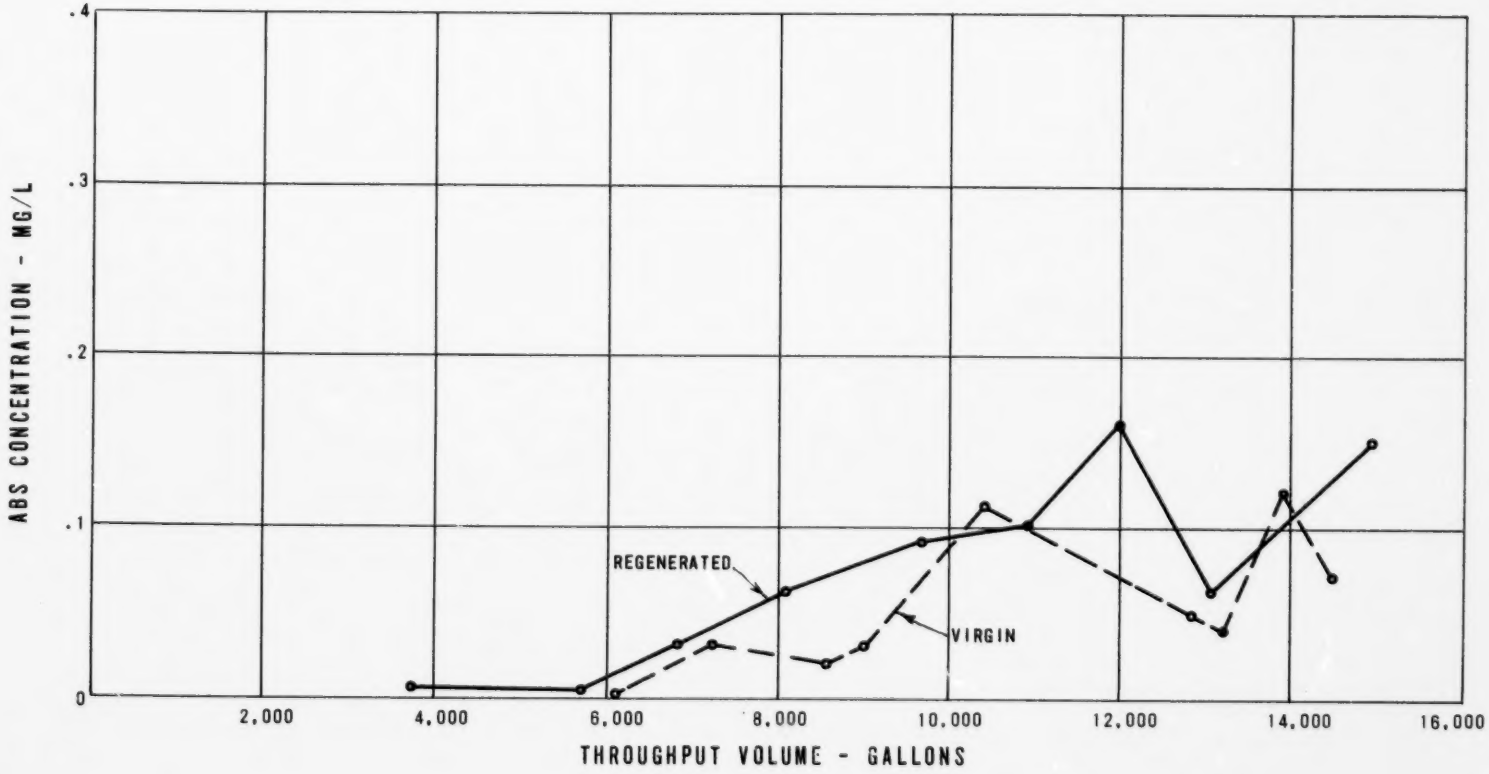


FIGURE 26

COMPARISON OF VIRGIN AND 1ST CYCLE REGENERATED CARBON

ABS PROFILE FOR 9.25 FT. CARBON DEPTH

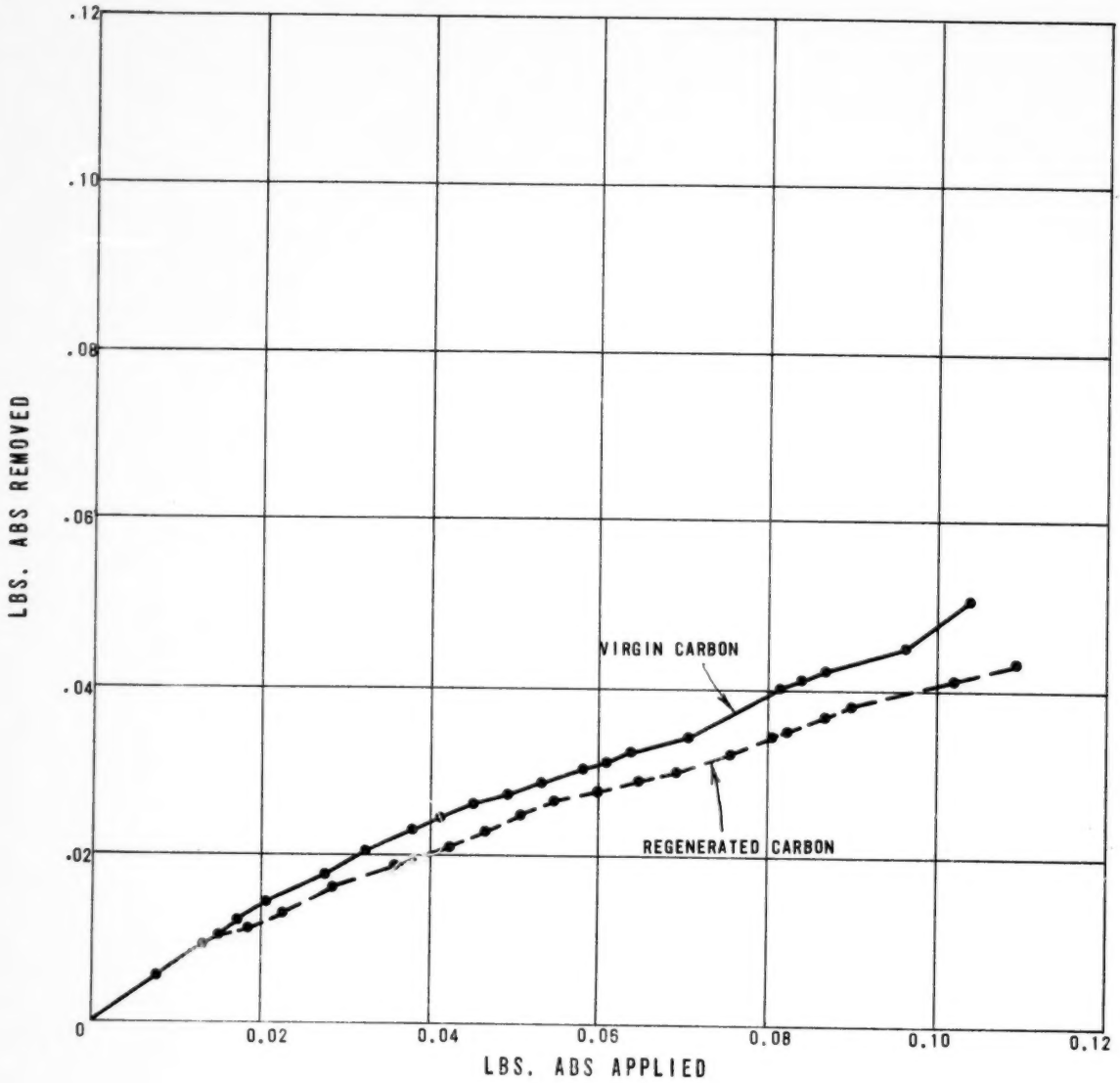


FIGURE 27
ABS ADSORPTION FOR
VIRGIN AND REGENERATED CARBON
1.75' CARBON DEPTH, 2.8 MINUTE CONTACT TIME

C3520.5

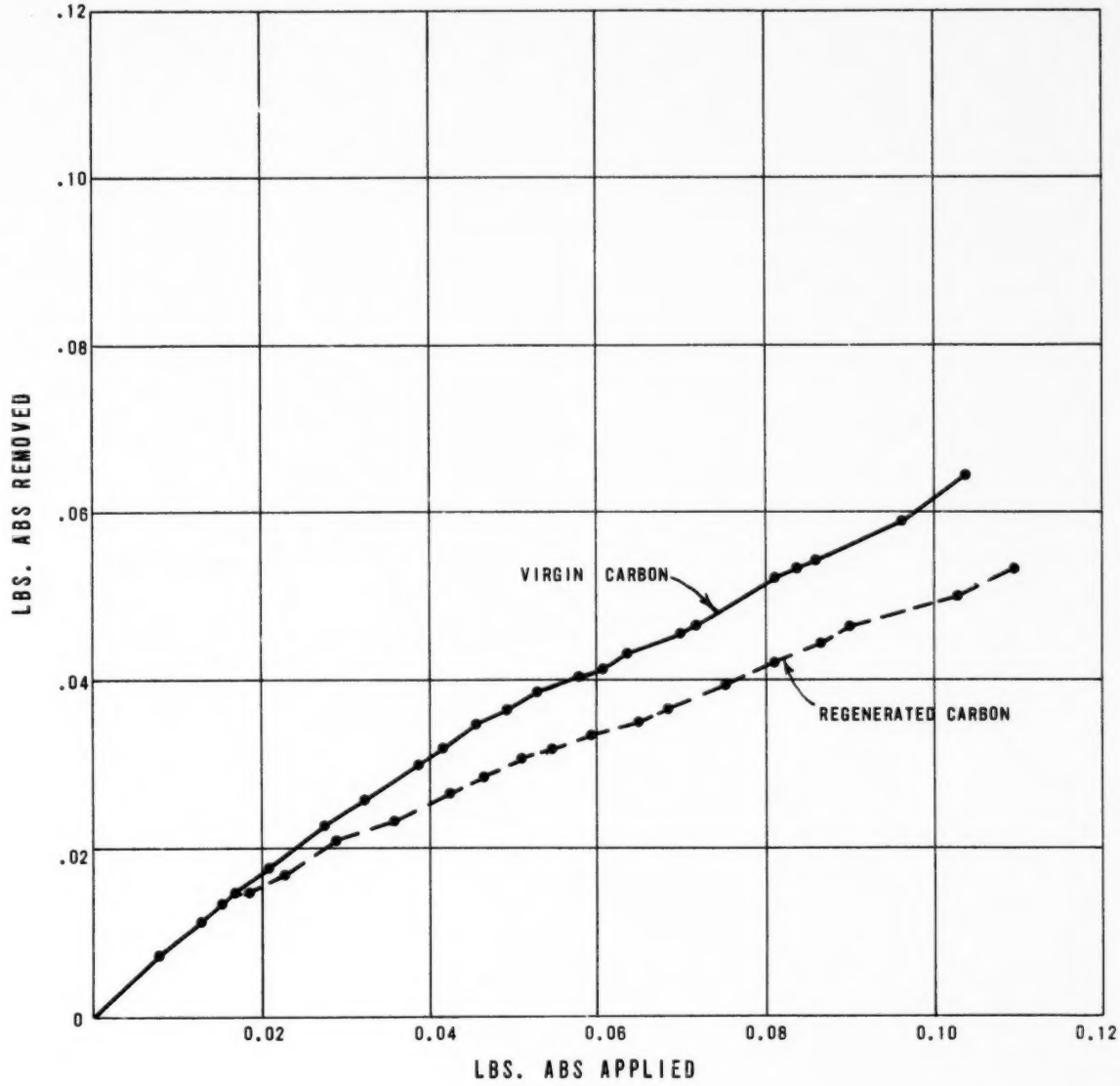


FIGURE 28
ABS ADSORPTION FOR
VIRGIN AND REGENERATED CARBON
4.25' CARBON DEPTH, 6.9 MINUTE CONTACT TIME

C3520.5

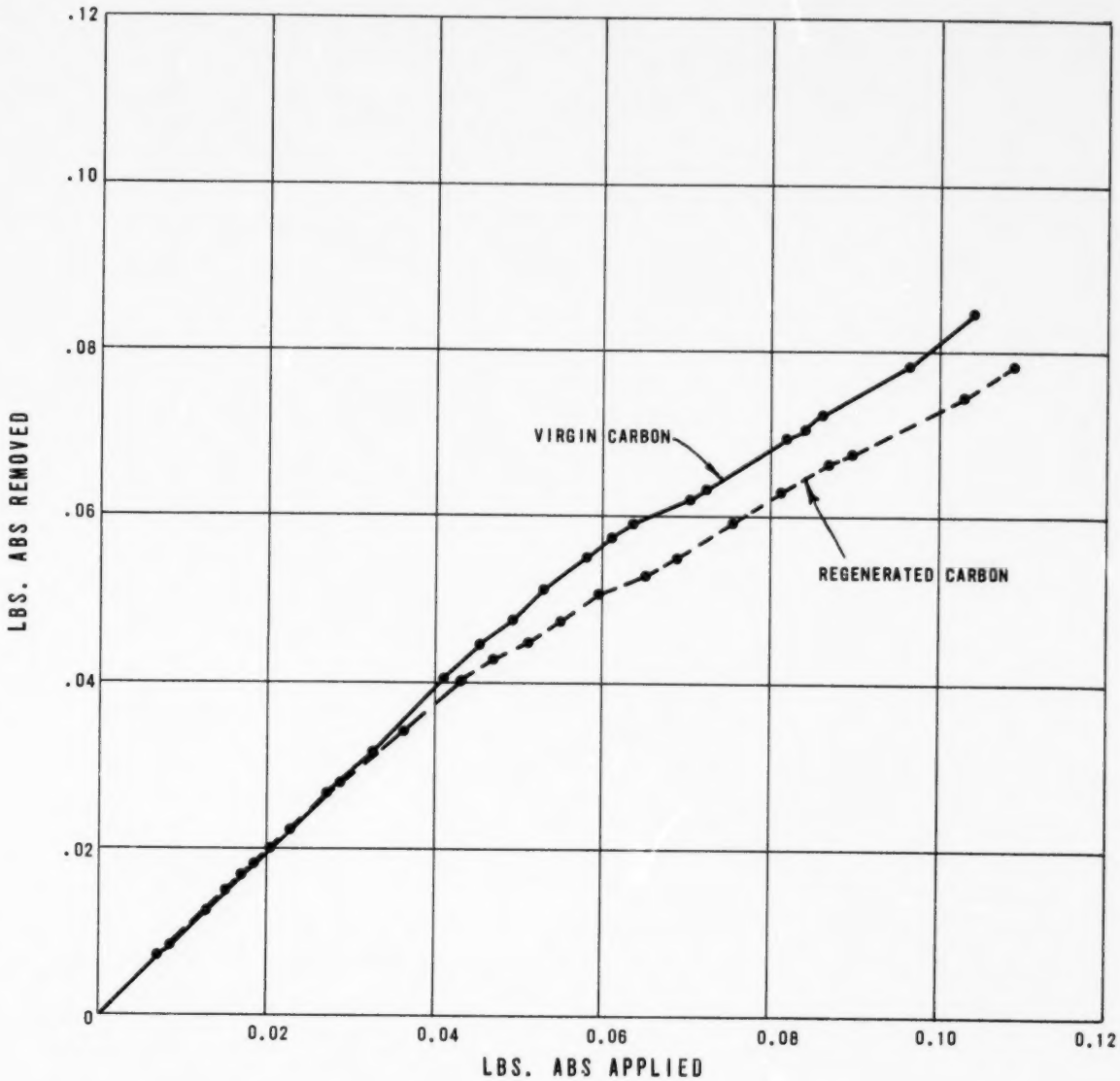


FIGURE 29
ABS ADSORPTION FOR
VIRGIN AND REGENERATED CARBON
6.75' CARBON DEPTH, 11 MINUTE CONTACT TIME

C3520.5

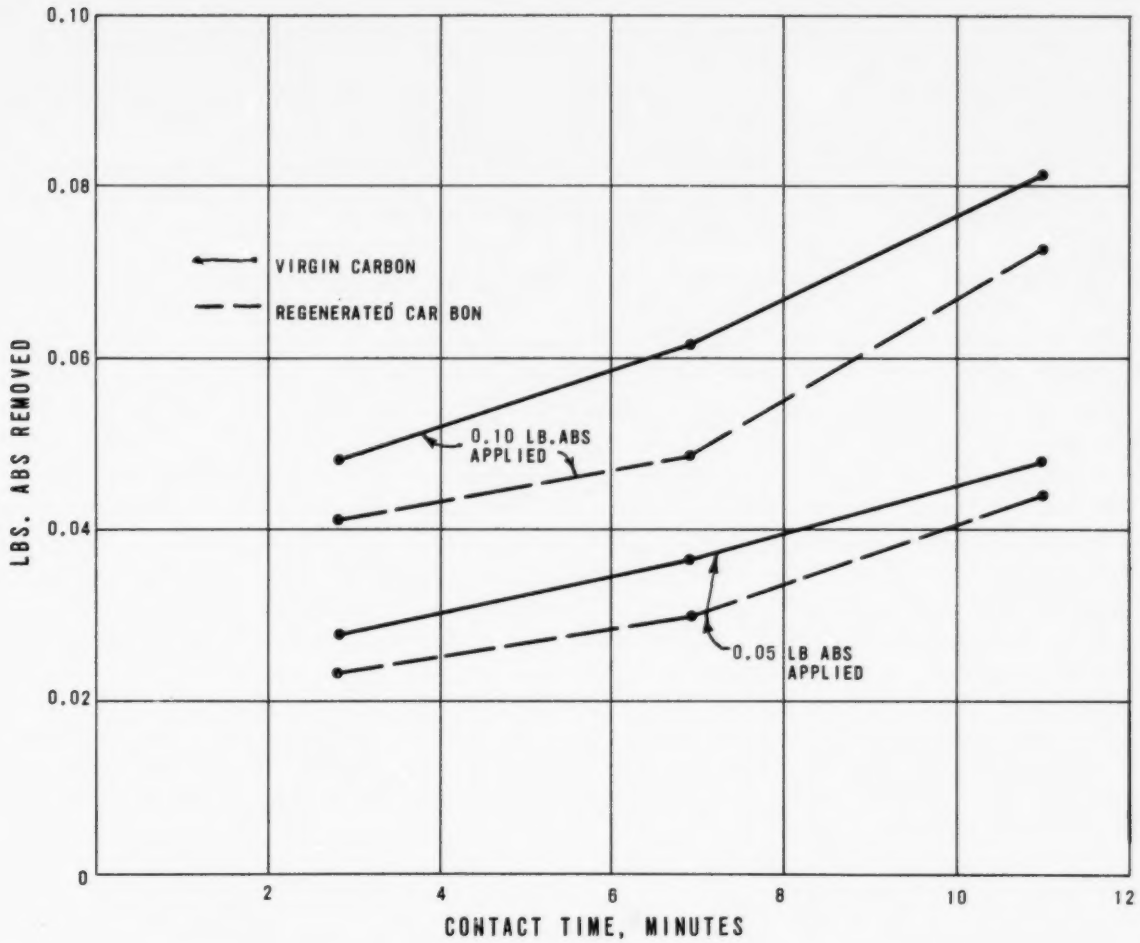


FIGURE 30

COMPARISON OF VIRGIN AND 1ST CYCLE REGENERATED CARBON FOR ADSORPTION OF ABS AS A FUNCTION OF CONTACT TIME

C3520.5

CARBON REGENERATION

Description of Regeneration System. A flow sheet of the plant scale carbon regeneration system is shown on Figure 31. When the carbon column effluent reaches the minimum effluent standards, spent carbon is removed from the column. These minimum water quality standards are as follows:

ABS	0.50 mg/l
COD	25 mg/l
Color	5 units
TOC	7.5 mg/l

Spent carbon is withdrawn and transferred in a slurry to the spent carbon drain and feed tanks by means of unchlorinated plant effluent. The carbon feed tanks are equipped with a screened drain to facilitate dewatering the carbon. After the carbon is dewatered, the carbon is fed to the furnace by a stainless steel screw conveyor.

Carbon regeneration takes place in a six-hearth, propane-fired, Pacific furnace, equipped with an afterburner and scrubber. The carbon flows downward through the six hearths in series. The hearths are numbered 1 to 6 from top to bottom. The capacity of the furnace is 6,000 pounds dry carbon per day. Burners are located on hearths 4 and 6 and are equipped with automatic temperature controllers. In addition, steam can be supplied to hearths 4 and 6.

The regenerated carbon discharges into the quench tank. The carbon is pumped from the quench tank by diaphragm pumps to the carbon defining tanks. The carbon is washed for one hour and is then moved hydraulically to the top of the carbon columns.

Under normal operation, a surplus carbon inventory is maintained. This permits bypassing the carbon columns for only a very short period of time while spent carbon is replaced by fresh carbon. In addition, this procedure does not require firing the furnace everytime carbon is withdrawn from the columns. To accomplish this, two concrete carbon storage bins have been provided, one to store spent carbon and the other to store regenerated and makeup virgin carbon.

Following the second regeneration of activated carbon, sand was added to each furnace hearth on the recommendation of the carbon manufacturer. The sand forms a layer between the hearth floor and the rabble arms on each hearth. A layer of sand is thus left on each hearth at the end of each regeneration rather than a layer of carbon which would be burned to ash. Sand is used in this manner to reduce carbon losses in furnaces used for carbon production.

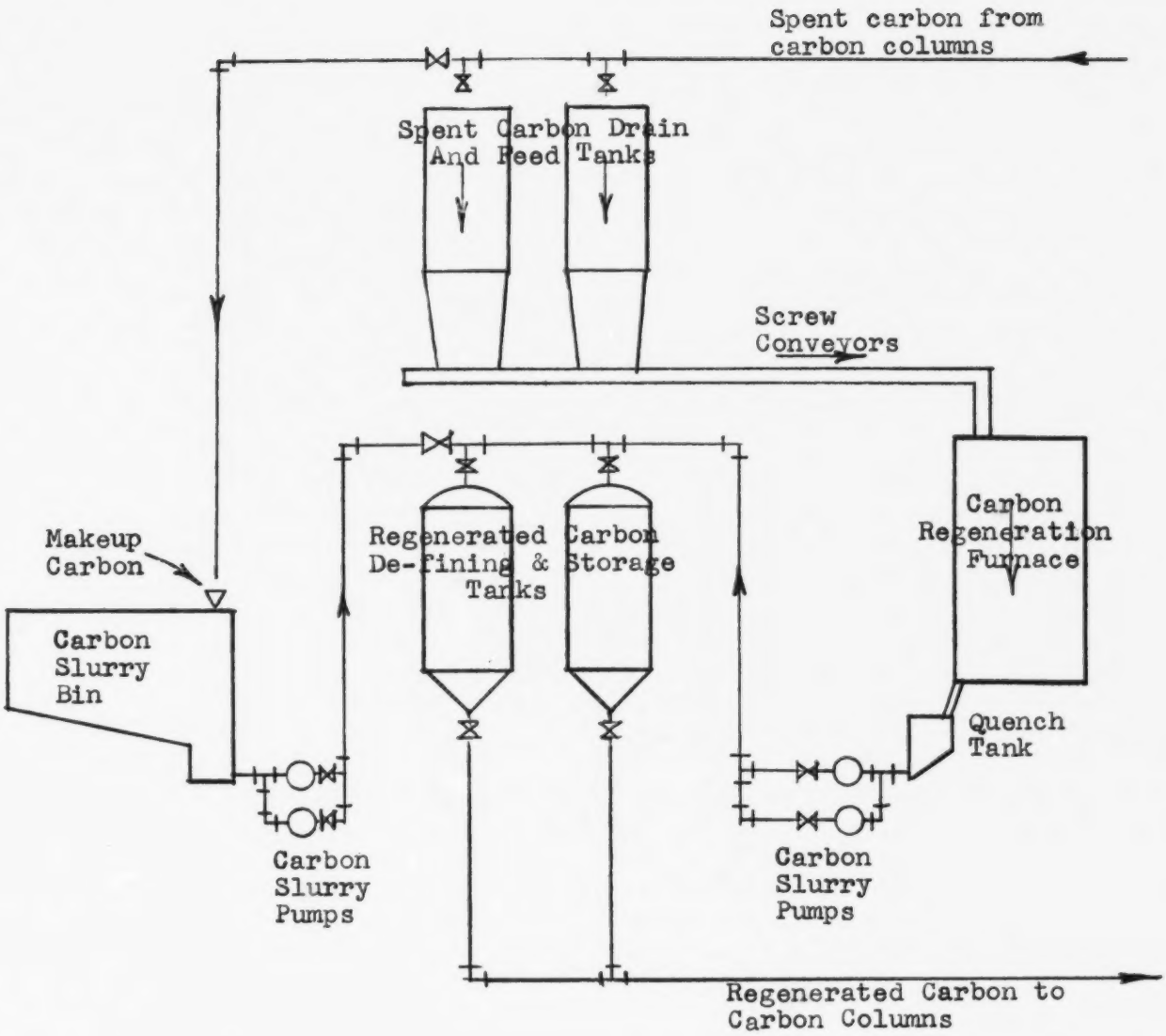


FIGURE 31

CARBON REGENERATION SYSTEM

C3520.5

Carbon Regeneration Data

Time Required for Dewatering of Carbon. Samples of spent carbon were obtained from the carbon feed bins at a depth of 2 feet below the carbon surface when the feed to the furnace commenced. The time allowed for dewatering varied from 1 to 26 hours. The percent moisture on a wet basis varied from 40.3 to 43.7 percent. In addition, samples were obtained at the point of discharge into the furnace and analyzed for moisture. The results fell within the range previously mentioned. It can be concluded that the dewatering of granular activated carbon can be obtained in one hour and that no apparent benefit can be realized at this time by retaining the carbon for an additional period of time.

Process Control Data. To date, approximately 84,000 pounds of carbon have been regenerated. Based upon the flow of 112 mg subjected to carbon treatment, the amount of carbon regenerated is equivalent to 740 pounds of carbon per million gallons of waste water treated. The contact time in the main carbon columns has averaged 15.4 minutes.

Carbon Furnace Operating Data. The results of the carbon regenerations to date are shown in Tables 6 and 7. The furnace was initially fired to a temperature of 1600° F. and carbon was fed at a rate of 240 pounds per hour (5,760 pounds per day). The burners on hearth 4 were set to deliver 4 percent excess oxygen and the burners on hearth 6, 2 percent excess oxygen.

When determining the benefit of adding steam to the furnace, the temperature was maintained at essentially 1600° F. and the feed at 240 pounds per hour.

By inspecting Table 6, and comparing the results of 9/17-1000 and 9/17-1400, the following may be concluded:

1. At a given temperature and feed rate, steam addition markedly reduced the apparent density (0.504 to 0.489) and increased the Iodine Number (887 to 911).

2. Steam addition gave a more uniform distribution of furnace hearth temperatures. Steam addition increased the temperatures of hearths 1, 2, and 3 by 200° F.

It was decided at this time that steam was to be used throughout the first few regenerations to study the efficiency of regeneration by varying steam, feed rate, and temperature. During these first few regenerations, one pound of steam was added per pound of dry carbon.

TABLE 6

CARBON REGENERATION DATA

DATE	TIME	ITEM	CARBON FEED LB DRY HR	BTU LB CARBON	APPARENT DENSITY	IODINE NUMBER	% ASH	FURNACE HEARTH TEMPERATURES - °F 1	2	3	4	5	6
9/16	1500	START FEED 1st WITHDRAWAL COL. 1 - NO STEAM											
		SPENT CARBON			0.536	715	4.46						
9/17	1000	REGENERATED COMPOSITE	240	3800	0.504	887	4.40	580	750	1090	1590	1500	1600
9/17	1030	START STEAM											
9/17	1400	REGENERATED COMPOSITE	240	3800	0.489	911	4.89	780	960	1270	1550	1480	1590
9/19	1830	START FEED 2nd WITHDRAWAL COL. 1 - WITH STEAM											
		SPENT CARBON			0.533	681	4.56						
9/20	0200	REGENERATED GRAB	400	2250	0.504	880		710	880	1170	1640	1520	1640
9/20	0900	REGENERATED GRAB	240	3800	0.497	935		810	1020	1240	1580	1460	1650
9/20	0900	START FEED PARTIALLY SPENT CARBON											
		SPENT CARBON			0.518	825							
9/21	0100	REGENERATED COMPOSITE	235	3920	0.491	915		750	950	1300	1650	1550	1650
9/21	0100	START FEED 3rd WITHDRAWAL COL. 1											
		SPENT CARBON			0.530	806							
9/21	0800	REGENERATED COMPOSITE	210	4400	0.490	935		720	900	1250	1640	1540	1650
9/22	0100	REGENERATED COMPOSITE	210	4400	0.490	915							
9/22	0100	START FEED 4th WITHDRAWAL COL. 1											
		SPENT CARBON			0.527								
9/23	0300	REGENERATED COMPOSITE	200	(4500)	0.485	900		840	1020	1250	1640	1540	1640
9/23	0300	START FEED 1st WITHDRAWAL COL. 2											
		SPENT CARBON			0.523	752							
9/24	0100	REGENERATED COMPOSITE	240	(3800)	0.486	954		820	990	1300	1640	1540	1670
9/24	0100	START FEED 2nd WITHDRAWAL COL. 2											
		SPENT CARBON			0.525								
9/25	0100	REGENERATED COMPOSITE	220	4150	0.489			870	1060	1270	1620	1560	1680
9/25	0100	START FEED 3rd WITHDRAWAL COL. 2											
		SPENT CARBON			0.519								
9/25	1800	REGENERATED COMPOSITE	240	3800	0.473	909		850	1030	1320	1620	1550	1670
10/13	2400	START FEED, BIN 2											
		SPENT CARBON	225	4110		843							
		REGENERATED COMPOSITE			0.495	938		1000	1200	1380	1640	1540	1660
10/15	0130	START FEED, BIN 1											
		SPENT CARBON	216	4250		766							
		REGENERATED COMPOSITE			0.486	922		880	1080	1380	1660	1580	1700
10/16	0330	START FEED, BIN 2											
		SPENT CARBON	204	4500		798							
		REGENERATED COMPOSITE			0.485	902		810	980	1220	1670	1590	1670
10/17	0700	START FEED, BIN 1											
		SPENT CARBON	248	3700	0.522								
		REGENERATED COMPOSITE			0.493	962		750	920	1260	1640	1580	1670
10/18	0600	START FEED, BIN 2											
		SPENT CARBON	238	3700									
		REGENERATED COMPOSITE			0.483	969		570	680	980	1630	1560	1660
10/19	0600	START FEED, BIN 1											
		SPENT CARBON	254	3860									
		REGENERATED COMPOSITE			0.480	969		740	910	1240	1620	1530	1640
10/19	1700	STOP 2ND REGENERATION											

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The following conclusions can be made about the effect of steam on carbon regeneration:

1. Steam gives a more uniform distribution of temperatures throughout the furnace.

2. A satisfactory degree of carbon regeneration can be obtained by adding one pound of steam per pound of dry carbon, maintaining a carbon feed of 5,760 pounds per day, and a temperature of 1650-1680° F. By operating at these temperatures, it is believed that burning of carbon and the subsequent carbon losses will be minimized.

Table 7 shows the properties of virgin, spent, and regenerated carbon. Thermal regeneration of granular activated carbon to essentially virgin characteristics was achieved as indicated by the apparent density and Iodine Number. No build-up of ash was observed during the first cycling of the carbon. The energy required to obtain this degree of activity averaged 4000 Btu per pound dry carbon at a temperature ranging from 1650-1680° F. with steam.

TABLE 7

PROPERTIES OF CARBON AT VARIOUS POINTS IN THE REGENERATION PROCESS

	Virgin Carbon	Spent Carbon	Carbon After One Regeneration With Steam
Apparent Density	0.481	0.519-0.536	0.473-0.497
Iodine Number	935	680-843	900-969
Ash-Percent	5.02	4.48	4.69

Carbon Losses. The cost of make-up carbon may constitute over 50 percent of the total cost of carbon treatment [10]. It is apparent that minimizing carbon losses is essential in order to operate an economical system. Sources of carbon losses include:

1. Shipping and handling.

2. Poor housekeeping.

3. Attrition in transferring carbon to and from the columns.

4. Coring carbon in the screw conveyor feeding the furnace.

5. Burning carbon in the furnace during regeneration and during procedures for startup and shutdown.

The most accurate method of determining carbon losses will be the measurements over a long period of time of the quantities of make up carbon on a weight basis to maintain the columns at the desired depth. Based upon this initial period of operation, the carbon loss has averaged less than 10 percent per regeneration. This loss is about twice the average experienced in the sugar industry and that found in pilot-scale regeneration of carbon used for treatment of sewage [9].

Sieve analyses were performed on the activated carbon at various points in the carbon transfer system and the regeneration process in order to evaluate any change in carbon particle size due to physical handling of the carbon. The results of the sieve analyses are shown in Table 8. A comparison of the data indicates that there was some loss of 8-mesh carbon when passed through the furnace (II vs III). The loss of 8-mesh carbon is balanced by a corresponding increase in the 16-mesh carbon size. Washing removed all particles finer than 200 mesh.

The data in Table 9 is the result of one set of sieve analyses. More data will be collected in order to arrive at some statistically valid conclusions with regard to carbon attrition due to physical handling.

TABLE 8

SIEVE ANALYSES OF CARBON AT VARIOUS POINTS IN REGENERATION SYSTEM

Item	Sampling Point	Percent Retained on Equivalent Screen Size							
		4	8	16	30	50	100	200	<200
I	Spent Carbon	0	9.2	63.1	25.4	2.0	0.1	0.1	0.1
II	Spent Carbon at Discharge into Furnace	0	10.5	60.2	25.9	2.7	0.2	0.2	0.3
III	Washed Regenerated Carbon	0	8.2	62.8	25.7	3.0	0.1	0.2	0
IV	Virgin Carbon	0	6.8	58.1	32.0	2.6	0.2	0.1	0.2

Total Cost of Carbon Treatment. The estimated cost of activated carbon treatment and the related pretreatment at the South Tahoe PUD plant is summarized in Table 9. The capital cost of the carbon system is higher than necessary for a plant with 2.5 mgd capacity because of the oversized carbon furnace which was provided in the Tahoe plant for future expansion. The furnace provided has capacity to regenerate the carbon required at the present dose to treat 7.5 mgd. The capital cost of the building, site preparation, etc., attributable to the carbon system was estimated by proportioning the total cost of the tertiary treatment plant on the basis of percentage of total plant area required for the carbon system.

The carbon regeneration cost, based on the period of inicial operation, can probably be reduced in the future. It is anticipated that the labor required can be reduced somewhat and that the carbon loss can also be reduced as the operating personnel gain experience in furnace operation. The addition of a sand layer to the furnace hearths should also decrease the carbon losses by reducing the amount of carbon burned in the furnace during each furnace startup and shutdown.

The cost of full-scale carbon treatment at South Lake Tahoe to date is less than that projected from pilot plant studies by Joyce et al [9], who estimated the cost of carbon treatment to be $70 per million gallons for a 10 mgd plant and $130 per million gallons for a 1 mgd plant. The cost of $67.80 per million gallons for the 2.5 mgd plant at Lake Tahoe is slightly less than that projected for a 10 mgd plant. The cost of the activated carbon treatment constitutes about 40 percent of the total cost of the tertiary treatment at South Lake Tahoe, as shown in Table 9.

TABLE 9

ESTIMATED COST OF ACTIVATED CARBON TREATMENT
AND RELATED PRETREATMENT AT
SOUTH TAHOE PUD WATER RECLAMATION PLANT

Activated Carbon Treatment			Cost Dollars/mg
Capital Cost			
Carbon Columns		$ 48,332	
Regeneration System		89,445	
Activated Carbon		35,154	
Piping and Valves		29,000	
Electrical and Controls		20,000	
Building, Site Preparation, Earthwork, Concrete, Roofing, Painting, Testing, Paving, Cleanup, Heating, Ventilating, Miscellaneous		107,208	
Total		$330,139	
Capital Cost Amortized at 4% over 20 years at 2.5 mgd			26.80
Regeneration Cost (6,000 lbs/day)			
Labor	$3.75/hr with 24 hr/day	$90.00/day	
Power	11 hp at energy charge of $0.008/kwh and demand charge of $2.30/kw	3.46/day	
Fuel	240 gals propane/day at $0.086/gal	20.60/day	
		$114.06/day	
		or	
		$ 0.019/lb	
With 10% Loss, Carbon Cost of $0.325/lb, Make-up Carbon Cost = $0.0325/lb Regenerated			
With Carbon Dose of 800 lbs/mg Regenerated Cost (0.019 + 0.0325) (800) =			41.20
Subtotal (Activated Carbon Treatment Cost)			$68.00

TABLE 9

Cost of Carbon Pretreatment (Separation Bed Process)	Cost Dollars/mg
Capital Cost	
$284,861 Amortized at 4% Over 20 Years at 2.5 mgd	22.80
Chemicals	
Alum (Dose for Phosphate Removal) 200 mg/l at $57.40/ton	47.60
Polyelectrolyte - 0.8 mg/l at $1.25/lb	8.35
Labor	
6 hrs/day at $3.75/hr for 2.5 mg	9.00
Power	
Based on 10 Minute Backwash Every 4 Hours at $0.008/kwh Energy Charge and $2.30/kw Demand Charge	10.50
Subtotal (Separation Bed Treatment)	98.25
Subtotal (Activated Carbon Treatment)	68.00
TOTAL COST OF TERTIARY TREATMENT	$166.25

ACKNOWLEDGMENTS

This study was supported in part by PHS Demonstration Grant 84-01. Members of the South Tahoe Public Utility District maintenance section assisted in the construction of the pilot carbon columns. Bill Chew and John Steward aided by performing most of the laboratory analyses and a portion of the data analysis. The California Department of Health performed the bacteriological analyses presented in Table 1. The R. A. Taft Sanitary Engineering Center, Public Health Service, performed the total organic carbon analyses reported herein. The Pittsburgh Carbon Company supplied the experimental 12 x 40 mesh carbon and their assistance was invaluable during the first carbon regeneration.

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